AD-A085 050 NAVAL POSTGRADUATE SCHOOL MONTEREY CA F/G 13/10
DEVELOPMENT OF A NONLINEAR 'D' TYPE BOILER MODEL.(U)
DEC 79 T D WALKER
UNCLASSIFIED NL

1 OF 1
AD A
085050

END
DATE
FILMED
7-80
DTIC

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

DEVELOPMENT OF A NONLINEAR "D" TYPE BOILER MODEL

by

Thomas Daniel Leclair Walker

December 1979

Thesis Advisor: T. M. Houlihan

Approved for public release; distribution unlimited.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO. AD-A085 050

3. RECIPIENT'S CATALOG NUMBER

9

4. TITLE (and Subtitle)

6

Development of a Nonlinear "D" Type Boiler Model.

5. TYPE OF REPORT & PERIOD COVERED

Master's Thesis, December 1979

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

10

Thomas Daniel LeClair Walker

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

Naval Postgraduate School
Monterey, California 93940

11

12. REPORT DATE

December 1979

13. NUMBER OF PAGES

~~91~~ 12 92

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Boiler Model, Shrink, Swell, Nonlinear Model, "D" Type Boiler.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A nonlinear digital model of a "D" type marine boiler is developed with emphasis on water level shrink and swell phenomena. Results indicate that further specifications of the phenomena are necessary before operational values of drum level are attained.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251450

DEVELOPMENT OF A NONLINEAR "D" TYPE BOILER MODEL

by

Thomas Daniel LeClair Walker
Lieutenant, United States Navy
BSEE, Purdue University, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1979

Author: Thomas D. L. Walker

Approved by:

Thesis Advisor

Paul J. Marto
Chairman, Department of Mechanical Engineering

William M. Tolles
Dean of Science and Engineering

ABSTRACT

A nonlinear digital model of a "D" type marine boiler is developed with emphasis on water level shrink and swell phenomena. Results indicate that further specifications of the phenomena are necessary before operational values of drum level are attained.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Recent developments in control theory and practice coupled with digital electronics advances have produced increased interest in digital power plant modeling. Although conventional marine boiler modeling is not a new concept, it is still an area of increased interest due to the relative lack of analytical data. This deficiency is due primarily to the extreme environment that must be endured by sampling equipment. Advances in data collecting and processing equipment have made boiler data collection practically feasible, and in fact, nuclear steam generator development depends heavily on actual data. However, it is not economically feasible for a single manufacturer to retrofit modern data collection systems on a standard marine boiler. The majority of marine boiler models available are not attractive from the control engineer's viewpoint because of one or more of the following:

a. The model is over-simplified to the point of being a "teapot" model.

b. The model is completely developed and written in Laplace transforms and the state space equations are too difficult to extract.

c. The model is over-complicated to the point of being computationally inefficient.

d. The causes and modeling of "shrink and swell" phenomena are ignored.

This model attempts to compromise between simplification and complication while including a theory and model for shrink and swell. The model follows the path specified by Fini [1] restated below:

a. A general D-type marine boiler model is prepared in Continuous System Modeling Program (CSMP) language.

b. A general FORTRAN program is used to prepare the initial conditions needed by the CSMP model.

c. The initial condition program depends only on data easily obtained from the manufacturer's technical manual and engineering handbooks.

II. MODEL CONSIDERATIONS

A. BOILER TYPE

The D-type boiler was chosen for modeling because of its comparative standardization among manufacturers coupled with its popularity in naval ship power plants. This particular boiler is one installed in the LHA-1 class of United States naval ships. Since D-type boilers operate under a wide range of geometry and output conditions the initial condition and model programs are designed to operate over similar ranges.

B. MODEL NOMENCLATURE

The model nomenclature differs from reference [1] because of a need to clarify the model equations and afford readability to the actual computer programs. The following objectives were considered when developing the nomenclature.

a. The equations must be easily read, necessitating minimum variable-definition referrals by the reader.

b. The notation used in the model development must be the same as that used in the computer programs.

The resulting notation combines a. and b. and consists of frequently used notations for variables followed by a subscript to indicate state point location and/or time using Figure 1.

Table 1, a tabulation of general rules and examples,

should suffice to allow the reader to follow the model development.

C. EQUATION DEVELOPMENT FORMAT

The dynamic model and initial condition programs are developed simultaneously with corresponding equations written in appropriate proximity to each other. A notation of [IC] following an equation indicates that it is an initial condition equation, while a notation of [ME] indicates a model equation. In some instances the equation applies to both programs, an indication of [IC, ME] is used to indicate this.

In as many instances as possible equations are developed directly from elementary heat transfer and fluid dynamic principles. This stems from a desire to encourage more research in this particular field and to foster a better understanding of marine boiler dynamics among students of marine engineering. The model was developed to be read and used by students with a minimum of additional research.

D. ASSUMPTIONS

Various assumptions are made to facilitate either model simplification or program tractability. The latter are not always desirable and further research or different programming techniques may obviate the need for them. The following major assumptions are made:

1. The energy transferred to the generating tubes is distributed uniformly, i.e. "even heating" exists.

2. There is a thorough mixing of the fluid in the steam drum.
3. Steam generation occurs only in the boiling section of the screen and main bank risers.
4. All generating tubes and downcomers in a particular circuit have the average geometry.

Uniform energy transfer is assumed to facilitate model simplification and is justifiable since the generating banks are designed to optimize uniform heat transfer. Mixing of the fluid in the drum is a result of the turbulence in the drum. The third assumption results from a lack of reliable experimental data and the knowledge that D-type boilers are natural circulation boilers relying on a density difference in the circulation loop to promote flow. Steam production outside of the generating banks would decrease the density difference, thus inhibiting natural circulation. The geometry assumption is necessitated by model simplification.

III. MODEL DEVELOPMENT

A. GENERAL

The boiler is developed from control volumes for which the appropriate equations for energy transfer and storage rates are written. The initial condition equations are generated by setting the rate (d/dt) terms equal to zero and solving for the desired variables.

The model is developed with three different elements:

1. Furnace-side heat transfer
2. Water-side heat transfer
3. Water-side circulation

B. FURNACE-SIDE HEAT TRANSFER

The gas flow path can be followed on Figure 1 where it is represented by the dashed line. The fuel and air mixture enters the furnace at state point Q where radiation heat transfer occurs to the screen riser tube metal. The flue gas then leaves the furnace and exchanges heat via convection with the superheater (state point R-S), main bank riser tubes (state points S-T), and economizer (state points T-U) in that order.

At state point Q the fuel-to-air ratio and fuel and air temperatures are relatively constant. This allows the sensible heat of the fuel and air to be lumped. The mass flow rate into the furnace is the sum of the air flow and fuel flow.

$$MQQ = MFQQ + MAQQ \qquad [ME]$$

The initial values of fuel and air flow at a specified operating point are known. Therefore, the corresponding initial condition equation is:

$$MQQ\emptyset = MFQQ\emptyset + MAQQ\emptyset \qquad [IC]$$

The mass flow rates through the remaining sections of the boiler are the same.

$$MQQ = MRR = MSS = MTT = MUU \qquad [ME]$$
$$MQQ\emptyset = MRR\emptyset = MSS\emptyset = MTT\emptyset = MUU\emptyset \qquad [IC]$$

The total heat supplied to the boiler can be written as the product of the mass flow rate of fuel and the "lumped" fuel heating value.

$$QQ = MFQQ * FHV \qquad [ME]$$

At a specific operating point the heat released to the furnace is available from the technical manual as is the furnace volume. The total heat input at steady state is the product of these two.

$$QQ\emptyset = QTOT\emptyset * FURVOL \qquad [IC]$$

This allows the computation of the fuel heating value.

$$FHV = QQ\emptyset / MFQQ\emptyset \qquad [IC]$$

1. <u>Furnace to Screen Risers</u>

The heat transfer to the furnace screen tubes occurs primarily through radiation, i.e.

$$q = \sigma A \left(T_{RR}^{4} - T_{VV}^{4}\right)$$

which is the Stefan-Boltzmann law[1] where σ is the Stefan-Boltzmann constant defined as:

$$\sigma = 2.8567 \times 10^{-11} \frac{BTU}{sec-ft^2-°R^4}$$

Therefore the heat transfer to the furnace screen can be written

$$Q1 = SIGMAA * ((TRR + 460.0) ** 4.0 - (TVV + 460.0) ** 4.0) \qquad [ME]$$

where

$$SIGMAA \equiv \sigma * A$$

At a given operating point, technical manual values are specified for the furnace heat absorption rate and the area of the radiant heat absorbing surface of the furnace screen. The product of these two yields the steady state heat transfer rate which in turn can be used to compute SIGMAA.

[1] This equation assumes that all the radiation from the combustion flame strikes the screen tubes, and both the flame and the tubes behave as black surfaces.

$$Q1\emptyset = QFURAB * ARAD \qquad [IC]$$

$$SIGMAA = Q1\emptyset / ((TRR\emptyset + 46\emptyset.\emptyset) ** 4.\emptyset - (TW\emptyset + 46\emptyset.\emptyset) ** 4.\emptyset)$$

An energy balance equation for the mass of flue gases in the furnace region can be written in the form

$$\frac{d}{dt}(m\,c_p\,T) = \text{total energy supplied} - \text{energy transferred to screen tubes} - \text{energy of gas leaving furnace region}$$

or

$$\frac{d}{dt}(MASSQR * CQR * TRR) = QQ - Q1 - MRR * CQR * (TRR - TAMB)$$

Note: TRR-TAMB is the absolute temperature. At steady state the rate terms are equal to zero. Values of total heat supplied to the boiler, heat transfer rate to the screen tubes, total flue gas flow rate, and flue gas temperature are available from previous equations. This allows the specific heat of the flue gas in the furnace region to be computed.

$$CQR = (QQ\emptyset - Q1\emptyset)/(MRR\emptyset * (TQR\emptyset - TAMB)) \qquad [IC]$$

During a transient, the density of the flue gas in the furnace and the specific heat of the furnace flue gas can be regarded as constants near a steady state operating point. The dynamic equation can be written as

$$DTRR = (QQ - Q1 - MRR * CQR * (TRR - TAMB)) / (MASSQR * CQR) \qquad [ME]$$

where

$$MASSQR = RFLUE * FURVOL \qquad [IC]$$

Thus,

$$TRR = \int_{t_1}^{t_2} DTRR + TRR\emptyset$$

or in CSMP-III language

$$TRR = INTGRL(TRR\emptyset, DTRR) \qquad [ME]$$

The value for TRRO is available from the technical manual.

2. Flue Gas to Superheater

For the remaining tube banks heat transfer occurs primarily through convection. The energy given up by the flue gas in flowing over the tube surfaces is represented by the general equation

```
energy     = mass flow  *  specific
given up     rate of       heat of
             flue gas      flue gas

           * change in temperature of the gas
```

i.e.

$$q = \dot{m} C_p \Delta T$$

At steady state, the energy transferred to the superheater tubes from the gas must equal the energy transferred from the tubes to the steam.

$$Q3\phi = Q4\phi \qquad [IC]$$

The steady state values for superheater inlet and outlet steam temperature and pressure are specified by the technical manual along with the superheated steam mass flow rate. This allows the direct computation of Q40 and Q30.

$$Q4\phi = MMM\phi * (HNN\phi - HMM\phi) \qquad [IC]$$

HMMO is the enthalpy of saturated steam corresponding to drum pressure, computed with curve fitted equations [2]. HNNO is available directly from the technical manual. The specific heat of the flue gas in the superheater region can now be computed.

$$CRS = Q3\phi / (MRR\phi * (TRR\phi - TSS\phi)) \qquad [IC]$$

Thus the dynamic equation for heat transferred from the flue gas to the tube metal is written:

$$Q3 = MRR * CRS * (TRR - TSS) \qquad [ME]$$

The heat transferred to the tubes via convection may also be represented by the Grimson correlation [3] which states that for cross flow over tubes;

$$\frac{hd}{k_f} = C\left(\frac{u_\infty d}{\nu_f}\right)^n Pr^{1/3}$$

where

u_∞ = velocity
d = tube diameter
C = constant
Pr = Prandtl number

Since h can also be written

$$h = q / A\Delta T$$

then

$$q = AC\left(\frac{u_\infty d}{\nu_f}\right)^n Pr^{1/3}\,\Delta T\left(\frac{K_f}{d}\right)$$

also

$$u_\infty = \frac{\dot{m}}{\rho A}$$

leading to the general equation

$$q = AC\left(\frac{d}{\nu_f \rho A}\right)^n Pr^{1/3}\,\dot{m}^n\,\Delta T\left(\frac{K_f}{d}\right)$$

Around a particular steady state operating point the physical properties can be regarded as a constant and the physical dimensions are constant, i.e.

$$AC\left(\frac{d}{\nu_f \rho A}\right)^n Pr^{1/3} = \text{constant}$$

which implies

$$q = (\text{constant}) * \dot{m}^n \Delta T$$

For flow over tube banks with differing rows of tubes and differing tube geometries the constant (n) varies little and the average is approximately .6 [3]. Therefore, in the case of the superheater and main bank riser tubes, the correlation is used in the form

$$q = C\dot{m}^{.6}\Delta T$$

or for the superheater

$$Q3 = KRS * MRR ** .6 * (TRS - TWW)$$

where TRS is the average flue gas temperature

$$TRS = (TRR + TSS)/2.\phi$$

Since the steady state values for Q30, MRRO, TRRO, TSSO, and TWWO are given by the technical manual the constant KRS can be calculated.

$$KRS = Q3\phi/(MRR\phi ** .6 * (TRS\phi - TWW\phi)) \text{ [IC]}$$

To provide the dynamic solution of superheater flue gas outlet temperature, the two transient equations for the flue gas to superheater tube metal heat transfer are equated resulting in

$$\frac{TRS - TWW}{TRR - TSS} = MRR^{.4} * CRS / KRS$$

where

$$TRS = (TRR + TSS)/2.\emptyset$$

Solving the above for TSS gives

$$TSS = (TRR * (PHI1 - 1) + 2 * TWW)/(PHI1 + 1) \quad [ME]$$

where

$$PHI1 = 2 * MRR ** .4 * CRS/KRS \quad [ME]$$

3. <u>Flue Gas to Main Bank Risers</u>

The equations for the flue gas to tube metal energy transfer in the main bank are derived similarly. For the equation involving flue gas specific heat;

$$Q5 = MSS * CST * (TSS - TTT) \quad [ME]$$

The Grimson correlation equation for the main bank risers is

$$Q5 = KST * MSS ** \emptyset.6 * (TST - TYY)$$

where

$$TST = (TSS + TTT)/2.0$$

By equating these two equations as was done with the superheater the flue gas temperature leaving the main bank can be written

$$TTT = (TSS \ast (PHI2 - 1) + 2 \ast TYY)/(PHI2 + 1) \quad [ME]$$

where

$$PHI2 = 2 \ast MSS \ast\ast 0.4 \ast CST/KST \quad [ME]$$

The steady state heat transfer is computed differently than that for the superheater. Since the steady state heat transfer to the screen bank has been computed, the energy transferred to the main bank is the difference between the total energy transferred and the desuperheater and screen bank energy transfer. At steady state the mass flow rate of steam out of the boiler is equal to the mass flow rate of feed in the boiler and the total energy transferred is the mass flow rate multiplied by the enthalpy change between the outgoing steam and incoming feedwater. Thus, the steady state energy transfer equation for the main bank is

$$Q60 = MMM0 \ast (HMM0 - HBB0) - Q20 - Q990 \quad [IC]$$

Q990 is computed in the water side heat transfer section.

Since Q50 = Q60 at steady state the heat transfer coefficient KST and the specific heat CST can be computed.

$$KST = Q50/(MSS0 \ast\ast 0.6 \ast (TST0 - TYY0)) \quad [IC]$$

$$CST = Q50/(MSS0 \ast (TSS0 - TTT0)) \quad [IC]$$

4. Flue Gas to Economizer

The economizer tubes differ from the generating and superheater tubes in that they are finned. A reasonable finned tube heat transfer correlation was developed by Weirmann, et al. [4]

$$j = \frac{h \, Pr^{2/3}}{C_p \, G_{max}}$$

G_{max} ≡ maximum mass flow rate

j ≡ correlation constant

C_p ≡ specific heat of flue gas

Since $h = \frac{q}{A \Delta T}$ the above correlation can be written

$$q = \frac{j \, A \, \Delta T \, C_p \, G_{max}}{Pr^{2/3}}$$

G_{max} is a function of mass flow rate into the tube bank and tube bank geometry. Similar to the case of the Grimson coefficient used for the superheater and main bank tubes the physical and geometric properties are considered constant leading to the use of the correlation in the form

$$q = C \dot{m} \Delta T$$

Therefore, for the economizer the equation is

$$Q7 = KTU * MTT * (TTU - TXX)$$

where

$$TTU = \frac{TTT + TUU}{2.\emptyset}$$

Paralleling the superheater and main bank, the heat transfer may also be written

$$Q7 = MTT * CTU * (TTT - TUU) \qquad [ME]$$

The steady state equation development follows that of the superheater and main bank sections and is not repeated here. The equations are:

$$Q8\emptyset = MAA\emptyset * (HBB\emptyset - HAA\emptyset) \qquad [IC]$$
$$Q7\emptyset = Q8\emptyset \qquad [IC]$$
$$CTU = Q7\emptyset/(MTT\emptyset * (TTT\emptyset - TUU\emptyset)) \qquad [IC]$$
$$KTU = Q7\emptyset/(MTT\emptyset * (TTU\emptyset - TXX\emptyset)) \qquad [IC]$$
$$TTU\emptyset = (TTT\emptyset + TUU\emptyset)/2.\emptyset \qquad [IC]$$

Knowing the values for KTU and CTU developed by the initial condition program allows the solution of the flue gas outlet temperature in the transient analysis. Thus,

[ME] $TUU = (TTT * (PHI3 - 1.\emptyset) + 2.\emptyset * TXX)/(PHI3 + 1.\emptyset)$

[ME] $PHI3 = 2.\emptyset * CTU/KTU$

C. WATER SIDE HEAT TRANSFER

1. Risers

The heat supplied to the riser banks is used both in the boiling and nonboiling length of the tube; however the assumption is made here that the heat transfer is all under fully developed flow boiling conditions. Since the nonboiling length of the risers is relatively small, little error is produced. For fully developed nucleate flow boiling, Levy [5] suggests the equation

$$Q = \frac{A\ P_{sat}^{4/3}}{1.782 \times 10^{6}}\ \Delta T_{sat}^{3}\ \ \frac{BTU}{sec-ft^{2}}$$

By lumping the constant area and denominator the riser equations can be written in the forms

$$Q = C * PSAT^{4/3} * \Delta TSAT^{3}$$

Therefore, the two riser equations are

$$Q2 = KV * PSAT ** (4.\emptyset/3.\emptyset) * (TVV - TSAT) ** 3.\emptyset \quad [ME]$$

and

$$Q6 = KY * PSAT ** (4.\emptyset/3.\emptyset) * (TYY - TSAT) ** 3.\emptyset \quad [ME]$$

for the screen and main bank respectively. A simple energy balance on the tube metal yields the metal temperatures, i.e.,

$$mass * C_p * \frac{dT}{dt} = q_{in} - q_{out}$$

The equations for screen and main bank metal temperatures are:

$$DTVV = (Q1-Q2)/(MASSV * CPV) \qquad [ME]$$
$$TVV = INTGRL(TVV\emptyset, DTVV) \qquad [ME]$$
$$DTYY = (Q5-Q6)/(MASSY * CPY) \qquad [ME]$$
$$TYY = INTGRL(TYY\emptyset, DTYY) \qquad [ME]$$

The heat transfer coefficient KY can be computed directly from tube geometrical data available in the technical manual;

$$KY = AREAMB/1.782E\emptyset6 \qquad [IC]$$

Since Q10 = Q20 at steady state, the dynamic equation for Q20 can be solved in a steady state situation for KV,

[IC] $KV = Q1\emptyset/(PSAT**(4/3)*(TVV\emptyset-TSAT)**3.\emptyset)$

Q60 was computed in Section III-B.3. This allows the calculation of the initial main bank riser tube metal temperature,

[IC] $TYY\emptyset = (Q6\emptyset/(KY*PSAT**(4/3)))**(1/3)+TSAT$

In the case of the screen risers, the initial tube metal temperature is available from the technical manual and the initial heat transfer rate has been previously calculated. This allows the calculation of the screen riser steamside heat transfer coefficient,

[IC] $KV = Q1\emptyset/(PSAT**(4.\emptyset/3.\emptyset)*(TVV\emptyset-TSAT)**3.\emptyset)$

2. Desuperheater

The Dittus-Boelter correlation [6] is used to compute the heat transfer rate from the steam to the desuperheater tubes. This correlation in its basic format is

$$Nu = .\emptyset 23 \, Re^{0.8} Pr^{n}$$

where

Nu	=>	Nusselt number
Re	=>	Reynolds number
Pr	=>	Prandtl number
n	=>	.3 (for cooling fluid)

When the appropriate variables and constants are substituted for the dimensionless numbers, the Dittus-Boelter correlation can be written

$$Q = K\dot{m}^{.8} \Delta T$$

where the constant K is defined as:

$$K = .\emptyset 23 * \frac{\text{thermal conductivity}}{\text{tube diameter}} * \text{heat transfer area}$$

$$* \left(\frac{4}{\pi * \text{tube diameter} * \text{viscosity} * \text{nr of tubes}}\right)^{.8}$$

$$* \; Pr^{.3}$$

and ΔT is the log-mean-temperature difference (LMTD).

Thus, for the desuperheater, the equation is

$$Q9 = KNP * MNN ** .8 * LMTONP$$

KNP can be computed directly. Thus,

$$KNP = ((.023 * THCONN)/DNP) * (4.0/(PI * DNP * VISCON * NTUBDS)) ** 0.8 * PRAN ** 0.3 * AREADS \quad [IC]$$

The energy given up by the steam to the tubes may also be written in terms of steam specific heat, flow rate, and temperature difference.

$$Q9 = CNP * MNN * (TNN - TPP) \quad [ME]$$

Similarly since the heat transfer to the water in the drum is totally by convection;

$$Q99 = KZ * (TZZ - THH) \quad [ME]$$

For initial condition calculations THH is considered to be equal to TSAT. Therefore

$$KZ = Q990/(TZZ0 - TSAT) \quad [IC]$$

The desuperheater outlet temperature is solved by equating the two dynamic equations for Q9 and solving for the desired outlet temperature.

$$TPP = (TNN - TZZ)/(EXP(KNP/(CNP * MNN ** 0.2))) + TZZ \quad [ME]$$

The instantaneous desuperheater tube metal temperature is obtained by an energy balance on the tube metal similar to that for the riser tube metal.

$$mass * C_p * \frac{dT}{dt} = q_{in} - q_{out}$$

Solving the appropriate equation for dT/dt results in

DTZZ = (Q9-Q99)/(MASSZ * CPZ) [ME]

TZZ = INTGRL (TZZ0, DTZZ [ME]

The specific heat of the steam in the desuperheater (CNP) may be calculated using the known steady state values for desuperheated steam flow rate and the desuperheater inlet and outlet temperatures and pressures.

Q90 = MNN0 * (HNN0 - HPP0) [IC]

CNP = Q90/(MNN0 * (TNN0 - TPP0)) [IC]

With the value of Q90 computed the initial log-mean-temperature difference can be calculated.

LMTDNP = Q90/(KNP * MNN0 ** 0.8)

The log-mean-temperature difference is a function of steam temperature in, tube metal temperature, and steam temperature out; therefore the initial tube metal temperature may be calculated.

$$TZZ\emptyset = (TNN\emptyset - EXPODS * TPP\emptyset)/(1.\emptyset - EXPODS) \quad [IC]$$
$$EXPODS = EXP((TNN\emptyset - TPP\emptyset)/LMTONP) \quad [IC]$$

3. <u>Economizer</u>

Paralleling the desuperheater development the Dittus-Boelter correlation is used to relate the heat transfer from the tube metal to the feedwater. Thus,

$$Nu = .\emptyset 23\, Re^{0.8} Pr^{n}$$

the only difference being that n is now .4 vice .3 because the fluid is now being heated. The appropriate constants are again lumped yielding

$$Q8 = KX * MAA ** \emptyset.8 * LMTDAB$$

An energy balance on the water gives the heat absorbed in two other forms;

$$Q8 = MAA * (HBB - HAA)$$
$$Q8 = MAA * CAB * (TBB - TAA) \quad [ME]$$

At the specified operating point the inlet and outlet conditions of the economizer as well as the mass flow rate are given, allowing the computation of the steady state heat transfer.

$$Q8\emptyset = MAA\emptyset * (HBB\emptyset - HAA\emptyset) \quad [IC]$$

The heat transfer coefficient KX is computed directly.

$$KX = ((.\phi 23 * THCONA)/DAB) * (4.\phi/(PI * DAB * VISCOA * NTUBEC)) ** \phi.8 * PRAA ** \phi.4 * AREAEC \quad [IC]$$

This permits the solution of the steady state log-mean-temperature difference.

$$LMTDAB = Q8\phi/(KX * MAA\phi ** \phi.8) \quad [IC]$$

Following the identical path delineated for the desuperheater, the tube metal initial temperature can be computed.

$$TXX\phi = (TAA\phi - TBB\phi * EXPOEC)/(1.\phi - EXPOEC) \quad [IC]$$

$$EXPOEC = EXP((TBB\phi - TAA\phi)/LMTDAB \quad [IC]$$

An energy balance on the economizer tube metal yields its instantaneous temperature.

$$DTXX = (Q8 - Q7)/(MASSX * CPX) \quad [ME]$$

$$TXX = INTGRL(TXX\phi, DTXX) \quad [ME]$$

By equating the formulations for Q8 involving LMTD and specific heat, the economizer outlet temperature may be calculated.

$$TBB = (TAA - TXX)/(EXP(KX/(CAB * MAA ** \phi.2))) + TXX \quad [ME]$$

The specific heat of the feedwater in the economizer is calculated at steady state using the computed value of steady state heat transfer and the given mass flow rates and inlet and outlet temperatures.

$$CAB = Q8\emptyset/(MAA\emptyset * (TBB\emptyset - TAA\emptyset)) \quad [IC]$$

4. <u>Superheater</u>

The development of the superheater equations follows that of the desuperheater and economizer and for that reason the development will not be repeated. The equations are listed below.

$$Q4 = CMN * MMM * (TNN - TMM) \quad [ME]$$

$$Q4\emptyset = MMM\emptyset * (HNN\emptyset - HMM\emptyset) \quad [IC]$$

$$CMN = Q4\emptyset / (MMM\emptyset * (TNN\emptyset - TMM\emptyset)) \quad [IC]$$

The initial superheater log-mean-temperature difference is computed directly allowing the subsequent calculation of the tube-metal-to-steam heat transfer coefficient used in the Dittus-Boelter equation.

$$LMTDMN = (TNN\emptyset - TMM\emptyset)/(ALOG((TWW\emptyset - TMM\emptyset)/(TWW\emptyset - TNN\emptyset))) \quad [IC]$$

$$KW = Q4\emptyset/(MMM\emptyset ** \emptyset.8 * LMTDMN) \quad [IC]$$

An energy balance on the tube metal yields the instantaneous tube metal temperature, the initial tube metal temperature being available from the technical manual.

```
DTWW = (Q3-Q4)/(MASSW * CPW)      [ME]
TWW  = INTGRL (TWWØ, DTWW)        [ME]
```

The superheater outlet temperature can now be calculated.

```
TNN = (TMM -TWW)/(EXP (KW/(CMN * MNN* *
      Ø.2))) + TWW                [ME]
```

D. WATER-SIDE CIRCULATION

1. General

The water/steam side circulation equations are by far the most difficult to visualize and codify. These equations must be accurate in order to predict phenomena such as shrink and swell while appropriate assumptions and simplifications must be made in order to make the equations tractable.

As can be seen in Figure 1, the feedwater enters the economizer at state point A, passes through the economizer to the steam drum where it becomes part of the water volume. The liquid leaves the drum via the downcomers, both main bank and screen at state points G and C respectively. The main bank downcomer delivers its liquid to the main bank risers via the water drum, and the main bank risers deliver the fluid to the steam separators. The flow through the screen risers is the same with the exception that there is no water drum in this circuit. The steam separators separate the majority of

the water from the steam leaving the drum at state point M and the majority of the steam from the water being discharged back into the drum liquid. The steam, with a negligible amount of water passes through the superheater via state point M-N. At the outlet of the superheater the steam leaving at path III is used for "main" steam; that leaving via path II travels to the desuperheater where it is cooled, then leaves via state point P and is used for auxiliary steam.

The water leaving the separators with a small amount of entrained vapor is mixed with the incoming feed water and forms a "foaming" vapor/liquid mass in the bottom half of the drum. The liquid from this mass leaves via the downcomers and is circulated through the loop.

2. Downcomer Pressure Drop

A closer look at the downcomer flow is necessary to justify assumptions that are made in the development of the pressure-drop equations.

Circulation ratio is defined as the ratio of the total weight of steam liberated to the drum [7]. For a 600 pound marine boiler this circulation ratio is on the order of 20:1 [7 and 8]. This implies that for every 21 pounds of liquid flowing down the downcomers, 20 pounds of it has already traveled up the riser and is at saturation temperature. Therefore, assuming the downcomers are perfectly insulated, it is reasonable to assume that the downcomer liquid is at or very near saturation temperature.

The momentum equation for the downcomers may be written:

pressure at top - pressure at bottom
= frictional loss - gravitational head
+ entrance loss + bend loss
+ exit loss + inertia force

The inertia force term may be considered negligible [9]. This is the quasistatic approximation which basically states that pressure waves move much more rapidly through the system than the important time constants. This is mathematically equivalent to the elimination of a large negative eigenvalue. This quasistatic approximation is only good for on-line transients and does not apply for extremely large discontinuities which would result in the boiler being taken out of operation, (e.g., a ruptured tube). Therefore the downcomer momentum equation can be written:

pressure at top - pressure at bottom
= (friction factor * downcomer length
÷ downcomer diameter + entrance factor
+ bend factor + exit factor)
* (downcomer mass flow rate)^2 ÷ (2 * (downcomer cross sectional area)^2 * density of fluid in downcomer * g_c) - density of fluid in downcomer * gravitational acceleration * height of downcomer ÷ g_c

In the model notation

```
PCPD = (FCD * LCD/DCD + ENTRCD + BENDCD
       + EXITCD) * MCC ** 2.0/(2.0 * ACD ** 2.0
       * RHOCD * GC) - RHOCD * G * ZCD/GC
```

```
PGPH = (FGH * LGH/DGH + ENTRGH + BENDGH
       + EXITGH) * MGG ** 2.0/(2.0 * AGH ** 2.0
       * RHOGH * GC) - RHOGH * G * ZGH/GC
```

for the screen and main bank downcomers respectively. FCD and FGH are friction factors of the form

$$f = 1/(1.74 - 2 \log (R/KS))$$

where R is the pipe radius and KS is the relative sand roughness [11].

```
FCD = 1.0/(1.74 - 2.0 * ALOG10(KSCD))   [IC,ME]
FGH = 1.0/(1.74 - 2.0 * ALOG10(KSGH))   [IC,ME]
```

3. Riser Pressure Drop

The momentum equation for the riser boiling section must take two phase flow effects into account because the flow in the boiling section is not homogeneous. Thus, there is a relative velocity between the liquid and vapor phases here. The steam separators are included in the riser length. However,

the effective length of the separators and thus the pressure drop are considered negligible because of a general lack of information concerning these items.

The pressure drop due to single phase or homogeneous flow in the nonboiling riser section can be written

$$\Delta P_{SPF} = \Delta P_{acceleration} + \Delta P_{friction} + \Delta P_{gravity}$$

$$\Delta P_{acceleration} = \frac{\dot{m}^2}{g_c * A^2} * \frac{(\rho_{out} - \rho_{in})}{\rho_{out} * \rho_{in}}$$

$$\Delta P_{friction} = \frac{4 * f * length * \dot{m}^2}{g_c * D * (\rho_{out} + \rho_{in}) * A^2}$$

$$\Delta P_{gravity} = \frac{g * height * (\rho_{out} + \rho_{in})}{2 * g_c}$$

Experiments conducted by Babcock and Wilcox [10] indicate that these homogeneous flow pressure drops may be modified to give the appropriate two phase flow pressure drops using correction factors that are functions of outlet quality and operating pressure. The two phase flow pressure drop can be written;

$$\begin{aligned} \Delta P_{TPF} = {} & \Delta P_{acceleration} * r_{acceleration} \\ & + \Delta P_{friction} * r_{friction} \\ & + \Delta P_{gravity} * r_{gravity} \end{aligned}$$

where the r terms are two phase flow correction factors available by using curve fits of the data from reference [10].

The form of these r terms become:

```
RGRAVE = 24.794 * XFF0 ** 2.0 - 6.5066 * XFF0 + .9776          [IC]
RGRAVK = 24.794 * XLL0 ** 2.0 - 6.5066 * XLL0 + .9776          [IC]

RACLE  = 15.4564 * XFF0 ** 2.0 + 18.4944 * XFF0 - .00007       [IC]
RACLJ  = 15.4564 * XLL0 ** 2.0 + 18.4944 * XLL0 - .00007       [IC]

RFRICE = -34.0822 * XFF0 ** 2.0 + 23.7164 * XFF0
         + .8734                                               [IC]

RFRICK = -34.0822 * XLL0 ** 2.0 + 23.7164 * XLL0               [IC]
         + .8734
```

Therefore, in the boiling region of the riser

$$\Delta P_{TPF} = \frac{\dot{m}^2 r_{acl}}{g_c \rho_{in} A^2} + \frac{2 f \,(\text{boiling length})\, \dot{m}^2 r_{fric}}{g_c \,(\text{diameter})\, \rho_{in} A^2} + \frac{g\,(\text{height of boiling region})\, \rho_{in}\, r_{grav}}{g_c}$$

The total pressure drop across the length of the riser is;

$$\Delta P = \Delta P_{SPF} + \Delta P_{TPF}$$

In model notation the equations are

```
PDPF= (MDD**2.Ø*(RHOEE-RHODD))/(GC*RHOEE*
      RHODD*ADE**2.Ø)+(4.Ø*FDE*LDE
      *MDD**2.Ø)/(GC*DDE*(RHODD+
      RHOEE)*ADE**2.Ø)+(G*ZDE*(RHODD
      +RHOEE))/(GC*2.Ø)+(MDD**2.Ø*
      RACLE)/(GC*RHOEE*AEF**2.Ø)+
      (2.Ø*FEF*LEF*MDD**2.Ø*RFRICE)/
      (GC*DEF*RHOEE*AEF**2.Ø)+
      (G*ZEF*RHOEE*RGRAVE)/GC


PJPL =(MJJ**2.Ø*(RHOKK-RHOJJ))/GC*RHOKK*
      RHOJJ*AJK**2.Ø)+(4.Ø*FJK*MJJ**
      2.Ø*LJK)/(GC*DJK*(RHOJJ+RHOKK)*
      AJK**2.Ø+G*ZJK*(RHOJJ+RHOKK)/
      (GC*2.Ø)+(MJJ**2.Ø*RACLK)/
      (GC*RHOKK*AKL**2.Ø)+(2.Ø*
      FKL*LKL*MJJ**2.Ø*RFRICK)/
      (GC*DKL*RHOKK*AKL**2.Ø)+
      (G*ZKL*RHOKK*RGRAVK)/GC
```

The friction factors are in the same form as those for the downcomers

```
FDE = 1.Ø/(1.74 - 2.Ø * ALOG1Ø (KSDE))        [IC]
FEF = 1.Ø/(1.74 - 2.Ø * ALOG1Ø (KSEF))        [IC]
FJK = 1.Ø/(1.74 - 2.Ø * ALOG1Ø (KSJK))        [IC]
FKL = 1.Ø/(1.74 - 2.Ø * ALOG1Ø (KSKL))        [IC]
```

At a specified steady state operating point the pressure drop across the downcomers must equal the pressure drop across the risers and the downcomer flow rate must equal the riser flow rate. Therefore by equating the appropriate pressure drop equations and solving the resultant relation for the flow rates, the initial flow rates may be computed as

```
MFFØØ = ((RHØCDØ * G * ZCD - G * ZDEØ * ((RHODDØ
        + RHOEEØ)/2.Ø) - G * ZEFØ * RHOEEØ *
        RGRAVE)/((FCD * LCD/DCD + ENTRCD +
        BENDCD + EXITCD)/(2.Ø * ACD * * 2.Ø
        * RHOCDØ) + ((RHOEEØ - RHODDØ)/
        (RHOEEØ * RHODDØ * ADF * * 2.Ø)) +
        (4.Ø * FDE * LDEØ * 2.Ø)/(2.Ø * DDF
        * (RHOEEØ + RHODDØ) * ADF * * 2.Ø) +
        RACLE/(RHOEEØ * ADF * * 2.Ø) + (4.Ø
        * FEF * LEFØ * RFRICE)/(2.Ø * DDF
        * RHOEEØ * ADF * * 2.Ø))) * * Ø.5    [IC]
```

```
MLLØØ = ((RHOGHØ*G*ZGH - G*ZJKØ*((RHOJJØ
        +RHOKKØ/2.Ø) - G*ZKLØ*RHOKKØ*
        RGRAVK)/((FGH*LGH/DGH + ENTRGH +
        BENDGH + EXITGH)/(2.Ø*AGH**2.Ø
        *RHOGHØ +(RHOKKØ - RHOJJØ)/
        (RHOKKØ*RHOJJØ*AJL**2.Ø)) +
        (4.Ø*FJK*LJKØ*2.Ø)/(2.Ø*DJL
        *(RHOKKØ + RHOJJØ)*AJL**2.Ø) +
        RACLJ/(RHOKKØ*AJL**2.Ø)+(4.Ø
        *FKL*LKLØ*RFRICK)/(2.Ø*DJK
        *RHOKKØ*AJL**2.Ø)))**Ø.5          [IC]
```

4. Riser Continuity

The relationship between the riser inlet and outlet mass flow rates is written in terms of the continuity equation for one dimensional unsteady flow,

$$\sum_{cs} \rho \bar{V} \cdot \bar{A} = -\frac{d}{dt} \int_{cv} \rho \, d\forall$$

In model notation, this becomes

```
MLL = MJJ - DRHOJL * VOLJL          [ME]
MFF = MOD - DRHODF * VOLDF          [ME]
```

The numerical differentiation technique used by CSMP-III is highly suspect, as are other techniques. An "averaging" system is used in the actual dynamic model. In addition, the flow rate down the downcomer and into the riser is held constant for the open loop boiler model.

5. Riser Quality and Density

The average density in the risers must be solved for explicitly. Linearly varying quality along the riser tube length follows directly from the assumption of uniform heat flux along the riser tube length. The average density along the tube length is the sum of the total change in density and the density entering divided by the riser tube length [1]. Assuming the density varies only in the boiling length of the riser, the total change in density can be written;

$$\int_{\text{boiling length}} \rho(\ell)\, d\ell$$

The average density is

$$\rho_{\text{average}} = \frac{1}{L}\left[\int_{\substack{\text{boiling}\\\text{length}}} \rho(\ell)\, d\ell + \rho_f * \text{nonboiling length}\right]$$

where ρ_f = density of saturated water

L = total tube length

Since $\rho(\ell)$ varies linearly from entering to exiting, $\rho(\ell)$ can be written in the form

$$\rho(\ell) = \frac{1}{V_f + \frac{X_{out}}{L_B}(\ell - LNB)V_{fg}} \qquad [1]$$

where V_f = specific volume entering

X_{out} = quality at riser outlet

L_B = boiling length

LN_B = nonboiling length

V_{fg} = change in specific volume from saturated liquid to saturated vapor

The integral of the explicit equation for $\rho(\ell)$ may be solved after rearrangement to

$$\rho(\ell) = \frac{1}{\left(V_f - \dfrac{X_{out}\, LN_B\, V_{fg}}{L_B}\right) + \dfrac{X_{out}}{L_B} V_{fg}\, \ell}$$

which is of the form $\dfrac{1}{a + b\ell}$

This yields the average density,

$$\rho_{av} = \frac{1}{L}\left[\frac{L_B}{X_{out}\, V_{fg}} \ln\left[\frac{X_{out}\, V_{fg}}{V_f} + 1\right] + \rho_f\, L_{NB}\right]$$

In model notation the formula is written

```
RHODFØ = (1.Ø/LOF)*(LEFØ/((XFFØ)*VFG)
         *ALOG(((XFFØ)/VF)*VFG + 1.Ø)
         +RHODDØ*LDEØ)                      [IC,ME]

RHOJLØ = (1.Ø/LJL)*(LKLØ/((XLLØ)*VFG)*
         ALOG((XLLØ*VFG)/VF + 1.Ø) + RHOJJØ
         * LJKØ                             [IC,ME]
```

To permit calculation of the quality term the energy balance on the liquid in the riser tubes is evaluated. Thus,

rate of change of riser energy = flow energy in - flow energy out + thermal energy in

$$\frac{d}{dt}(\rho h V) = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + q_{in}$$

If the enthalpy term is treated as the average enthalpy in the riser the equation may be written

$$\frac{d}{dt}\left(\rho\left(h_f + x_{out} * h_{fg}/2\right)V\right) = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + q_{in}$$

In model notation this is written in the form:

```
OHXLL = (MGG * (HJJ-HF-XLL*HFG/2.Ø) + Q6 -MLL
        * XLL * HFG/2.Ø)/(RHOJL * VOLKL)              [ME]
HXLL  = INTGRL(HXLLØ, OHXLL)                          [ME]
XLL   = (HXLL - HF) * 2.Ø/HFG                         [ME]
OHXFF = (MCC * (HOO-HF-XFF* HFG/2.Ø)+Q2
        -MFF * XFF * HFG/2.Ø)/(RHOOF * VOLEF)         [ME]
HXFF  = INTGRL(HXFFØ, OHXFF)                          [ME]
XFF   = (HXFF - HF)* 2.Ø/HFG                          [ME]
```

The initial conditions, HXLLO and HXFFO are calculated in the initial condition program.

The steady state equations for quality are derived differently. The energy transfer rate to the riser liquid may be written in the form

$$\dot{Q} = \dot{m}\,\Delta h$$

where

$$\Delta h = h_{out} - h_{in}$$
$$= h_f + x_{out} h_{fg} - h_{in}$$

Solving for X_{out} yields

$$x_{out} = (\dot{Q} + \dot{m}(h_f - h_{in})) / (\dot{m}\, h_{fg})$$

or

XFFØ = (Q1Ø + MFFØ * (HF - HDDØ))/(MFFØ * HFG) [IC]
XLLØ = (Q5Ø + MLLØ * (HF - HJJØ))/(MLLØ * HFG) [IC]

6. Riser Boiling Boundary Location

The nonboiling length of riser tube is the product of the riser tube length and sensible to total heat ratio [1]

$$L_{NB} = L\, q_s / q_t$$

The sensible to total heat ratio may be expressed as the enthalpy change in raising the water to saturated conditions divided by the total enthalpy change, i.e.

$$\frac{q_s}{q_t} = \frac{h_f - h_{in}}{(h_f + x_{out} h_{fg}) - h_{in}}$$

The equations for nonboiling length are

LOEØ = LDF * AMAX1((HF - HDDØ), Ø.Ø)/((HDDØ + XFFØ * HFG) - HDDØ) [IC]

LJKØ = LJL * AMAX1((HF - HJJØ), Ø.Ø)/((HJJØ + XLLØ * HFG) - HJJØ) [IC]

The Fortran function AMAX1 is used here because the above equations are used in an iterative loop in the initial condition program and there is a possibility during iterations of reaching a situation where the enthalpy entering is greater than saturation enthalpy. The final initial condition solution prevents this. The AMAX1 function is not used for the dynamic model. Thus,

$$LDE = LDF * (HF - HDD)/((HF + XFF * HFG) - HDD) \quad [ME]$$

$$LJK = LJL * (HF - HJJ)/((HF + XLL * HFG) - HJJ) \quad [ME]$$

The boiling volume is derived directly from the solution for the nonboiling length.

$$\text{boiling volume} = \text{total volume} * \frac{\text{boiling length}}{\text{total length}}$$ Hence,

$$VOLEF = VOLDF * LEF/LDF \quad [ME]$$

$$VOLKL = VOLJL * LKL/LJL \quad [ME]$$

7. Steam Drum Liquid Mass and Energy Balance

The rate of change of liquid mass within the drum is equal to the sum of the mass flow rates entering and leaving the drum. The liquid mass flowing into the drum is the saturated liquid from the risers, the liquid from steam condensation in the drum, and the incoming feedwater. The liquid leaving is that leaving via the downcomers. The dynamic model equation is

$$DDMASL = MLL * (1.\phi - XLL) + MFF * (1.\phi - XFF) + MCOND + MBB - MCC - MGG \quad [ME]$$

The instantaneous mass of liquid in the drum is

$$DMASL = INTGRL(DMASL\phi, DDMASL) \quad [ME]$$

where

$$DMASL\phi = (VOLDRM * RODRML)/2.\phi \quad [IC]$$

The drum energy balance is derived similarly, i.e.,

$$DDMOHL = MLL * (1.\phi - XLL) * HF + MFF * (1.\phi - XFF) * HF + MCOND * HFG + MBB * HBB - MCC * HCC - MGG * HGG \quad [ME]$$

The instantaneous drum energy is

$$DMOHL = INTGRL(DMOHL\phi, DMOHL) \quad [ME]$$

The initial drum energy is the product of the initial drum liquid mass and initial drum enthalpy.

$$DMOHL\phi = DMASL\phi * HDRUM\phi \quad [IC]$$

The initial drum liquid enthalpy is

$$DH = DMOHL / DMASL$$

In the dynamic model, drum liquid enthalpy is considered the enthalpy of saturated liquid.

The steam condensation rate equation is based on the difference between the pressure and temperature of the steam and that of the liquid [12]

$$\begin{aligned} MCOND = {} & 560.93 * (PMM/(TMM+460.0) ** 0.5 \\ & - PSAT/(TSAT+460.0) ** 0.5) + .02568 \qquad [ME] \end{aligned}$$

The water level in a marine boiler is generally considered in reference to a mid-drum zero, that is, a water level of plus one inch implies the water level is one inch above the drum centerline. For computational efficiency the assumption is made that for small changes in water level around the midpoint of the drum the water surface area remains constant. This allows a simplified level equation, i.e.,

$$LEVEL = (DMOV - VOLDRM/2.0)/(LSTMDM * DSTMDM) \qquad [ME]$$

DMOV is the equation for the total volume of "liquid" in the drum. Recalling that a small percentage of steam leaving the separators is entrained in the liquid, the rate equation for "liquid" volume in the drum is

$$\begin{aligned} DDMOV = {} & ((MFF+MLL-MBB) * VF + PCU * (MLL+MFF) \\ & * VV + MBB * VBB - (MCC+MGG) * VF \\ & + MCOND * VFG) \qquad [ME] \end{aligned}$$

where DMDVO is the volume occupied at time zero which is half the drum volume.

8. Circulation System Initial Condition Iteration Procedure

The initial conditions for the circulation system are found by flow rate balancing in the downcomer-riser flow loops. An initial guess of flow rate is made using the assumed riser exit quality of .05 percent which is reasonable for this type of boiler [7]. Coupling this assumption with the assumption that the percent carryunder is zero, an initial approximation of the flow rate can be determined using the figures for initial heat transfer rate to the risers calculated in Section III-A. Hence,

$$\text{mass flow rate} = \frac{\text{heat transfer rate}}{\text{assumed quality} * \text{latent heat of vaporization}}$$

A first approximation of downcomer enthalpy for both banks can be calculated. This downcomer enthalpy is assumed to be the same for all downcomers. Using an energy balance on the liquid in the steam drum

```
MFFØ  = Q1Ø/(XASUME * HFG)                          [IC]
MLLØ  = Q5Ø/(XASUME * HFG)                          [IC]
HCDØ  = ((MFFØ + MLLØ - MBBØ) * HF + MBBØ * HBBØ)/
        (MFFØ + MLLØ)                               [IC]
HGHØ  = HCDØ                                        [IC]
```

The screen riser inlet enthalpy is assumed to be equal to that of the screen downcomer; however the main bank fluid absorbs additional energy from the desuperheater located in that circuit. Therefore, the main bank riser inlet enthalpy

must be calculated separately. Thus,

$$HJJ\emptyset = HGH\emptyset + Q9\emptyset / MHH\emptyset \qquad [IC]$$

The downcomer density must be calculated for use in the pressure drop calculations. Hence,

$$VCO\emptyset = ((MFF\emptyset + MLL\emptyset - MBB\emptyset) * VF + MBB\emptyset * VBB\emptyset) / (MFF\emptyset + MLL\emptyset) \qquad [IC]$$

$$RHOCO\emptyset = 1.\emptyset / VCO\emptyset \qquad [IC]$$

$$RHOGH\emptyset = RHOCO\emptyset \qquad [IC]$$

The riser outlet quality is calculated using the initial quality formulation previously developed. This computation is followed by the calculation of the riser non-boiling and boiling lengths.

The average density of the risers is calculated along with the two phase flow multiplication factors for use in the flow rate/pressure drop calculation.

An updated flow rate is now computed and compared with the first approximation. If it is within a specified error criteria calculation stops. If not the previous approximation is updated and the calculations continued with the new approximation.

Upon completion of the flow rate balancing the initial flow rates in the downcomer/riser loops are known along with the riser outlet quality.

The steady state drum specific volume and density are computed as

$$VORML\phi = VCO\phi + PCu * VV$$
$$RODRML = 1.\phi / VORML\phi$$

The initial steam mass in the drum is then calculated as

$$OSTM\phi = VOLORM * RHOV / 2.\phi$$

9. Superheater Pressure Drop

All entrance, head, and exit losses are considered negligible in the superheater compared to the frictional pressure drop.

$$\Delta P = f \frac{L}{D} \frac{\dot{M}^2}{A^2 \rho_{average}}$$

By lumping the constants the pressure drop equation is

$$PMM - PNN = KON1 * MMM ** 2.\phi / RHOMN\phi$$

The following definitions apply here:

$$KON3 = (PMM\phi + PNN\phi)/(RHOMM\phi + RHONN\phi) \quad \boxed{IC}$$
$$RHOMN\phi = (RHOMM\phi + RHONN\phi)/2.\phi$$
$$KON1 = ((PMM\phi - PNN\phi) * RHOMN\phi)/MMM\phi ** 2 \quad \boxed{IC}$$

10. Steam Valve Equation

The flow through the steam valve is considered directly proportional to the outlet pressure and valve opening, i.e.,

$\dot{m}$ = C * P * (Valve Opening)

MMMIII = PNN * KON4 * VALVE [ME]

The constant is computed in the initial condition program.

KON4 = MMMIII /(VALVEØ * PNNØ) [IC]

E. EQUATIONS OF STATE

The equations of state listed below are used in both the initial condition and dynamic programs. With the exception of the subcooled specific volume equation used for the feedwater entering the drum, they are reasonably accurate in the 300-1500 psi range. The subcooled specific volume equation is accurate in the 600-800 psi range.

```
PSAT = EXP((ALOG(HSAT)-4.467Ø8)/.26452          [2]
TSAT = EXP((.22151 * ALOG(PSAT)+4.771[illegible]))      [2]
HSAT = EXP(Ø.26452 * ALOG(PSAT)+4.467Ø8)        [2]
HFG  = 922.15-Ø.4Ø516 * PSAT + 1.717E-Ø4
       * PSAT ** 2.Ø - 4.219E-Ø8 ** 3.Ø         [2]
RHOF = 63.8 - Ø.Ø1781 * TSAT + 1.132E-Ø5
       * TSAT ** 2.Ø - 6.786E-Ø8 * TSAT
       ** 3.Ø                                   [2]
VBB  = .Ø16ØØ488 - .ØØØØØ2Ø146 * TBB
       + 3.6511E-Ø8 * TBB ** 2.Ø
       - 8.142E-11 * TBB ** 3.Ø + 1.4Ø81E-13
       * TBB ** 4.Ø - 1.148E-16 * TBB ** 5.Ø
       + 8.034E-2Ø * TBB ** 6.Ø
```

IV. RESULTS AND CONCLUSIONS

A. GENERAL

A listing of the initial condition program and the dynamic boiler model program is given in Appendices A and B respectively. The initial condition program output data must be properly formatted for input to the CSMP-III dynamic model. In addition, because the dynamic model utilizes the liquid in the steam drum as a saturation state point from which all other state points are derived, two of the initial conditions must be modified to eliminate a discontinuity between the steady state program and the dynamic model. The equations involved and an explanation are given below.

```
DMASLØ = (VOLDRM * RHOCDØ)/2.Ø              [IC]
DMDHLØ = DMASLØ * HDRUMØ                    [IC]
DMDHL  = INTGRL(DMDHLØ,DDMDHL)              [ME]
DMASL  = INTGRL(DMASLØ,DDMASL)              [ME]
DH     = DMDHL/DMASL                        [ME]
```

As stated previously, the enthalpy of the liquid in the drum is considered saturation enthalpy. The dynamic model must begin with the rate of condensation in the drum (MCOND) as close to zero as possible. This is a natural steady state position - drum liquid and drum steam both at the same pressure and temperature. In order to insure this to be the case DMASLO and/or DMDHLO must be modified such that the initial

drum enthalpy (DH) very closely approximates the enthalpy of saturated liquid corresponding to the drum steam temperature and pressure (PMM and TMM). This is easily facilitated by the use of the CALL DEBUG statement in the dynamic program With this procedure:

1. The initial condition program is executed and the initial conditions formatted for CSMP-III use.
2. The dynamic model is executed for only a short run time, i.e. 5 seconds.
3. Observing the DEBUG output from the model, DMASLO and/or DMDHLO are modified such that PSAT and TSAT equal PMM and TMM.
4. The model is reexecuted for a short run to check. MCOND should be very small.
5. Since DH is implicitly related to PMM and TMM, the procedure may have to be repeated a few times. The objective is to force as many of the "DERIVATIVE" terms in the DEBUG output to comparatively small figures as possible.

The model as used operates satisfactorily with DMASLO = 8002.2 and DMDHLO = 3.96163E 06. This forces the initial MCOND term to .35949.

Because of the CSMP function DERIV used in the program, the model is extremely sensitive to integration time step. Numerical differentiation is not a desirable function to perform in a dynamic model; however attempts to explicitly differentiate the equations concerned failed. One solution

to the problem is to "smooth" the derivative function by averaging it over several timesteps. The model performed satisfactorily with a fixed-step integration procedure (Runge-Kutta), an integration time step of .04 seconds, and averaging the derivative over sixteen time steps.

B. OPEN LOOP RESPONSE

The open loop response to a ten percent increase in throttle opening is shown in Figures 2-7. As expected, the response of the main bank circulation loop and screen bank circulation loop is different. This is in keeping with the different purposes of those two loops, steam generation and furnace screening respectively. The effect of the valve opening increase is barely noticeable in the screen circulation loop.

The swell effect is not noticeable. Further conversations with Mr. Paul Weitzel at Babcock and Wilcox indicate that the percentage of "carry under" is not a constant as it was treated in this program. One to two percent is a good starting estimate for steady state; however during a transient "carry under" mass flow rate is computed by subtracting the amount of steam leaving the boiler from the amount of steam produced. This should always be a positive number. The vapor that does not leave the boiler is "carried under." The following program will implement this "carry under":

Modify the section of the dynamic model titled "COMPUTE THE DRUM SPECIFIC VOLUME" to read:

```
          PROCEDURE CRYUND=FILTR8(MMM)
          IF(TIME.GT.0.0)GO TO 45
          CRYUND=PCU*(MLL+MFF)
          GO TO 46
45        CRYUND=(MLL*XLL+MFF*XFF)-MMM
46        RISE1=DELAY (250,RISTIM,CRYUND)
          RISE2=CRYUND
          IF(VALUE.GT..51)GO TO 55
          RISE=RISE2
          GO TO 57
55        RISE=RISE1
57        CONTINUE
          ENDPROCEDURE
          DDMDV=((MFF+MLL-MBB)*VF+CRYUND*VV...
                +MBBØ*VBB-(MCC+MGG)*VF+MCOND...
                *VFG-RISE*VV)
```

Follow the above statements with the unmodified equations for DMDV.

The previous procedure was not implemented in the present dynamic model. The quality formulation in the present model is apparently too simplified and this causes a shortfall in quality at the outlet of the screen riser bank. As a result of this shortfall, there are instances during transient operation when the model is not "producing" as much steam as it is "using". Mr. Weitzel suggests using twenty node finite difference approximation for quality. This could be done using an equation for quality such as:

$$X = \frac{q}{A \rho_f V_{in} h_{fg}} z$$

where

X = quality

Z = distance up the riser (ft)

q = heat input to riser (BTU/s-ft)

A = cross sectional area of riser (ft^2)

ρ_f = density of saturated liquid (lbm/ft^3)

V_{in} = velocity of liquid entering (ft/s)

h_{fg} = latent heat of vaporization (BTU/lbm)

Simultaneously an implicit equation for continuity could be applied to produce a balanced mass flow rate without assuming that the downcomer mass flow rate remains constant.

C. CONCLUSIONS

The model presented is not a finished model. Further research is needed to successfully implement the shrink and swell theories presented. When the previously mentioned difficulty with riser outlet quality is solved, the model should approximate the dynamics of a wide range of D-type marine boilers depending on the initial conditions supplied to the initial condition program.

The initial condition program develops the initial conditions necessary for the detailed boiler model with the relatively scant data available from the boiler technical manual shown in Appendix C and a small amount of data from common engineering handbooks. Because of the relatively small amount of data required the initial condition program and/or the model can serve as a basis for a boiler condition monitoring system.

D. SUGGESTIONS FOR FURTHER RESEARCH

It is evident that the model suffers by using the CSMP-III function DERIV. In order to facilitate the explicit solution of the continuity equation for the riser banks some form of differentiation is required, either numerical or explicit. An explicit solution is much more desirable from a stability standpoint. A more detailed investigation with fewer assumptions might produce the correct form for the explicit differentiation equation. It should be noted, however, that when using explicit differentiation the model must average the derivative over at least two time steps to avoid the creation of an algebraic loop. This is easily done with the same PROCEDURE format used to average the derivative in the current model.

The use of small perturbation techniques to linearize the model and thus allow a state-space representation for multi-variable control development and analysis should be undertaken. There is a computer code available locally to facilitate this for CSMP models; however it does not accept the CSMP DERIV function and/or the averaging procedure. A means of bypassing this problem would result in a general D-type boiler model - applicable to a very wide range of boilers currently in use - which could be linearized about specific operating points. These individual models could then be used for the development and testing of multivariable control systems.

Using locally available optimizing computer codes, an optimal D-type boiler design could be attempted with regards to boiler geometry.

A more detailed analytical and experimental investigation of current D-type marine boilers should be undertaken locally. Little research has been done in this area and that which has been done has often been based on either an incorrect physical model of a marine boiler or on a nuclear steam generating plant. A starting point could be the data analysis of common horizontal and vertical steam separators followed by an optimum design for these elements. The improper and/or maintenance of drum internals apparently grossly affects boiler operation and water level stability during rapid transients.

TABLE 1
MODEL NOTATION

PRINCIPAL LETTER OR ACRONYM	MEANING	EXAMPLES
T	TEMPERATURE	TAA - temperature of fluid entering the economizer TAB - average temperature of fluid in the economizer TAAO - initial temperature of fluid entering the economizer
H	ENTHALPY	HDD - enthalpy of liquid entering the screen riser HDDO - enthalpy of liquid entering the screen riser at time zero
V	SPECIFIC VOLUME	VBB - specific volume of liquid at economizer outlet
X	QUALITY	XFF - quality at outlet of screen risers XLL - quality at outlet of main bank risers DXFF - time rate of change screen riser outlet quality
RHO	DENSITY	RHODD - density at outlet of screen downcomer RHOCD - average density in screen downcomer
M	MASS FLOW RATE	MGG - mass flow rate down main bank downcomer MRRO - mass flow rate of flue goas through the superheater at time zero
Q	ENERGY TRANSFER	Q1 - energy transfer from furnace flue gas to screen riser tube metal Q2 - energy transfer from screen riser tube metal to screen riser fluid

NOTE: In general, rate variables $\frac{d}{dt}$ are preceded by the letter D, i.e., DHXFF, DRHOJL.

SCHEMATIC DIAGRAM OF A
NAVAL BOILER

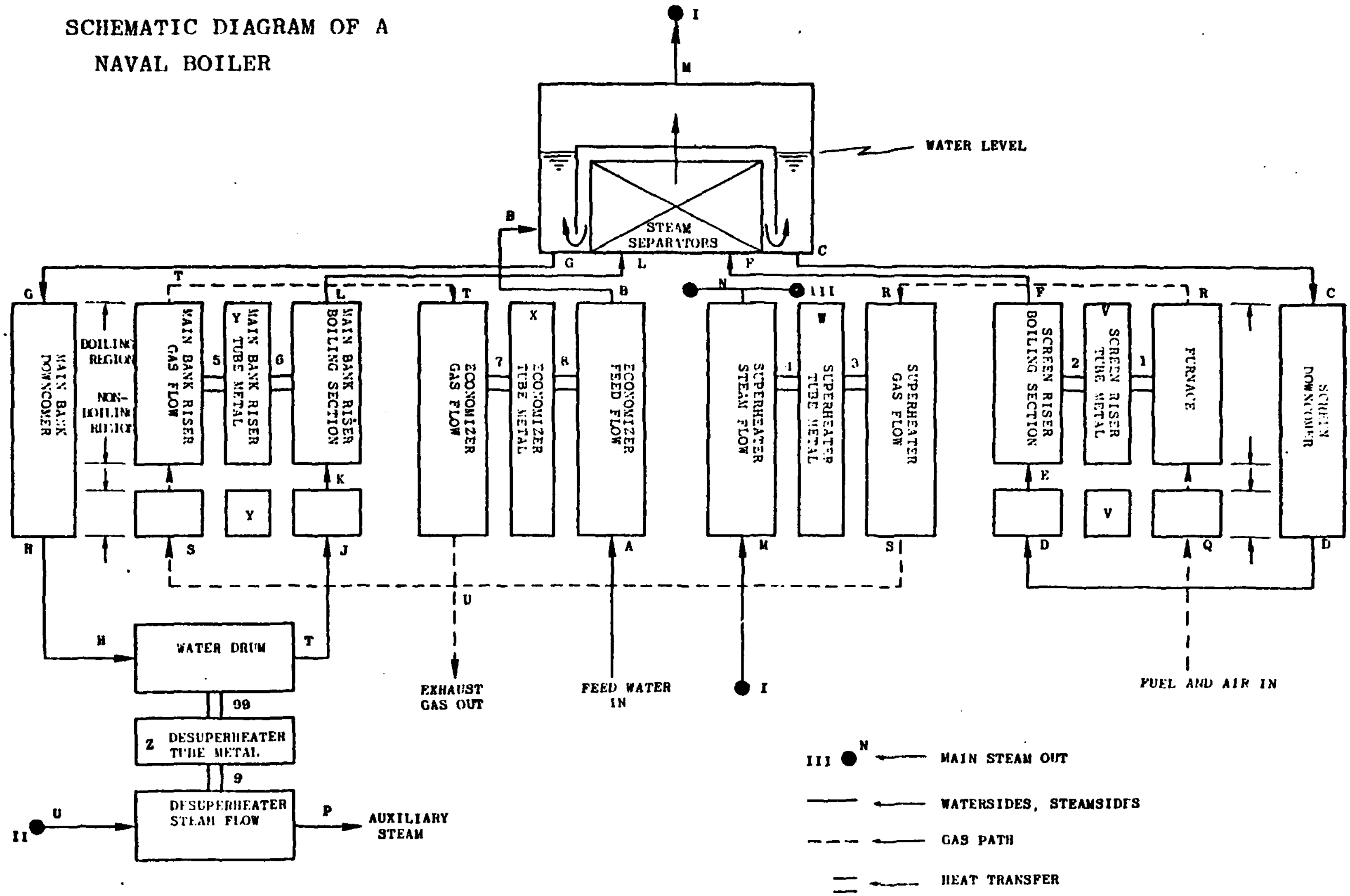


Figure 1.

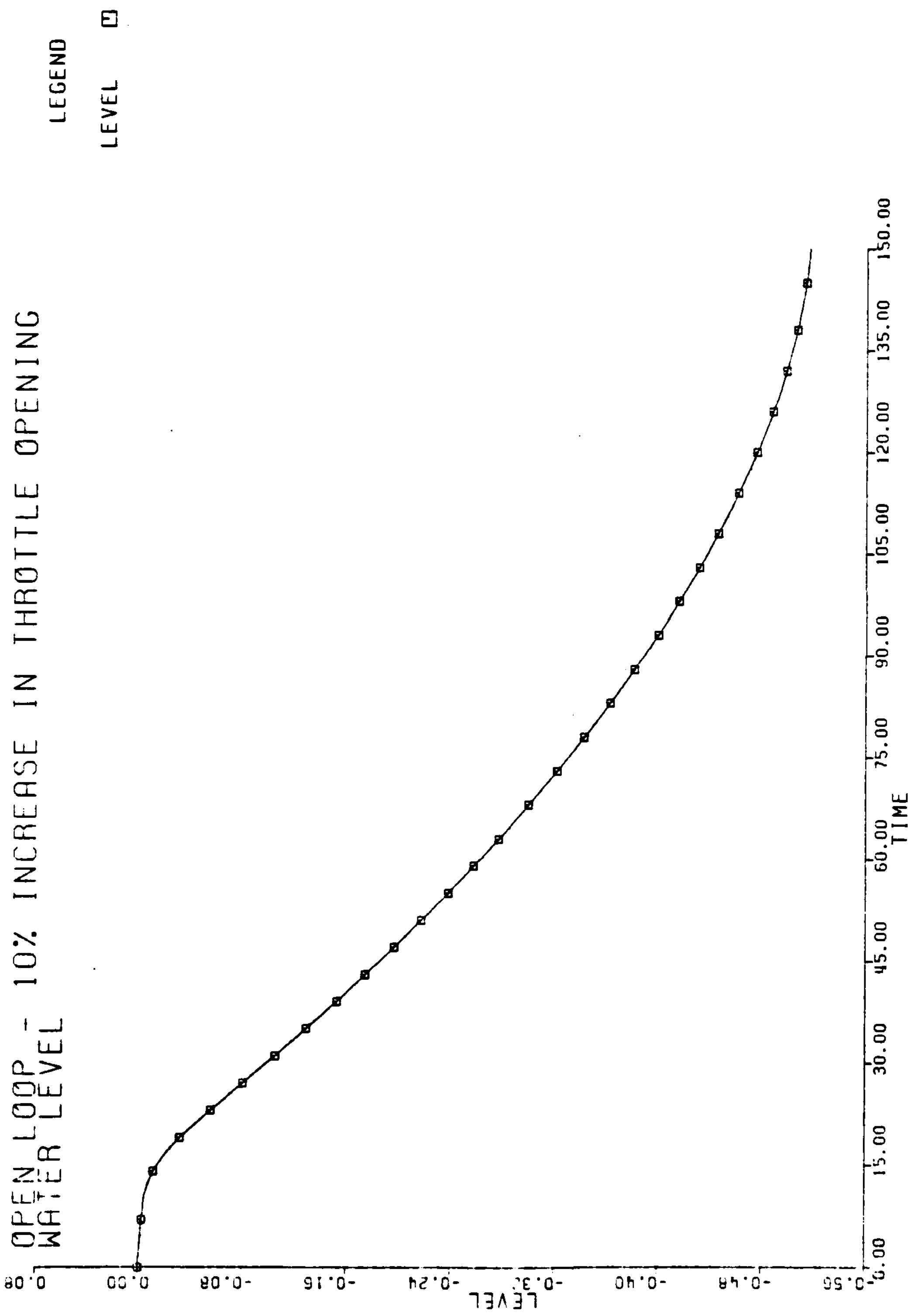

OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
WATER LEVEL
LEGEND
LEVEL
0.08
0.00
-0.08
-0.16
-0.24
-0.32
-0.40
-0.48
-0.56
LEVEL
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 2.

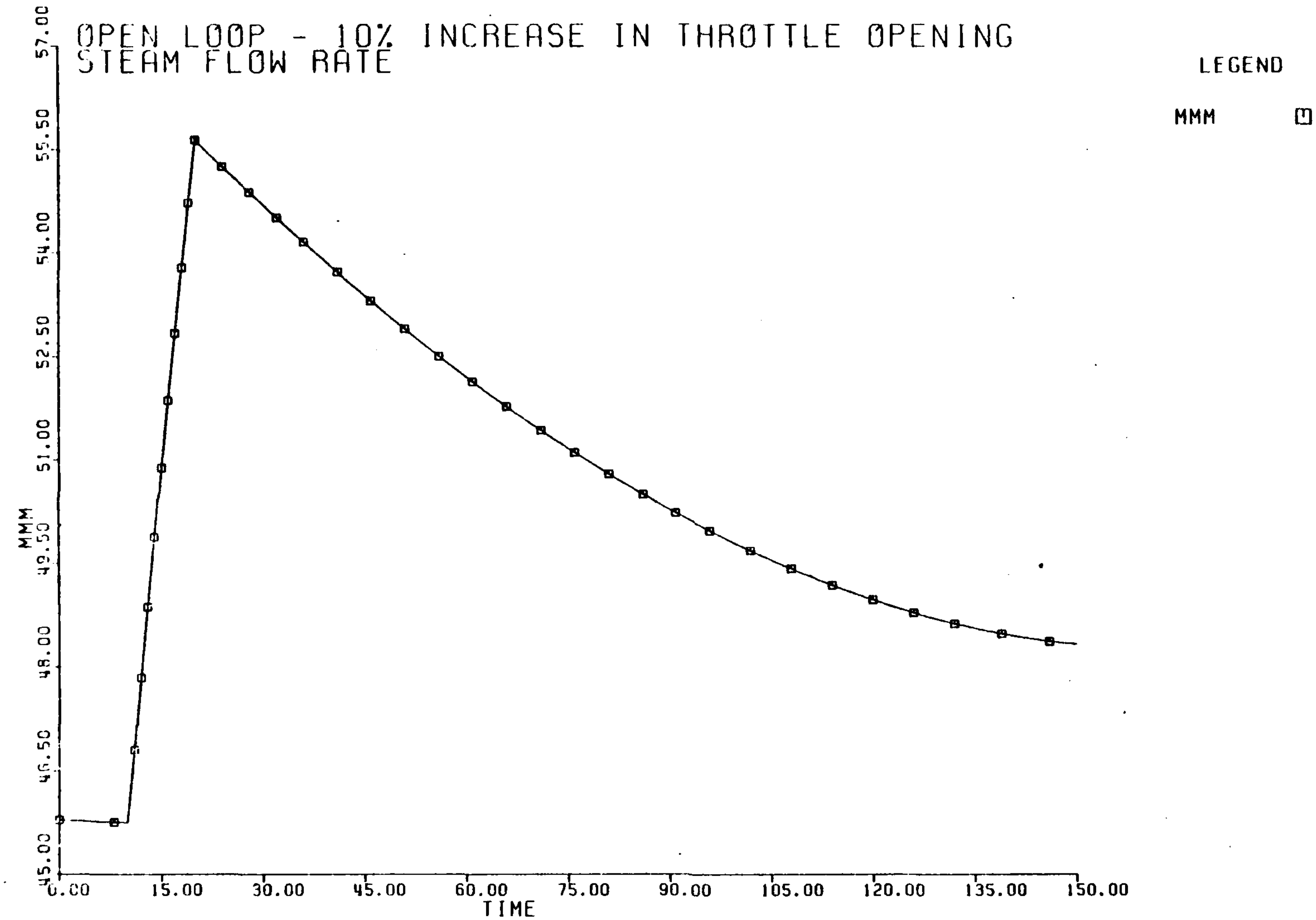

OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
STEAM FLOW RATE
LEGEND
MMM
MMM
TIME
45.00
46.50
48.00
49.50
51.00
52.50
54.00
55.50
57.00
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00

Figure 3.

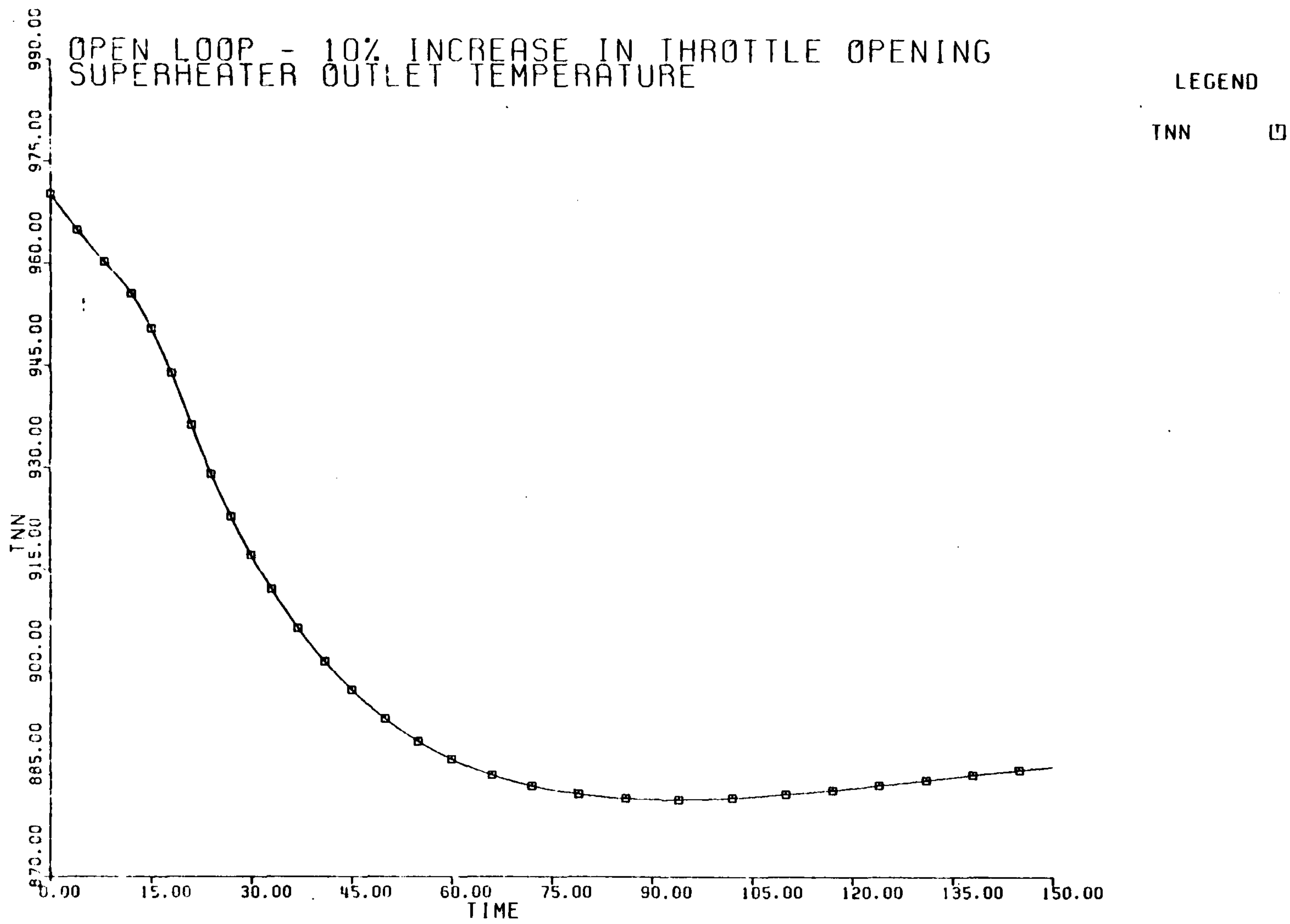

OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
SUPERHEATER OUTLET TEMPERATURE
LEGEND
TNN
990.00
975.00
960.00
945.00
930.00
915.00
900.00
885.00
870.00
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 4.

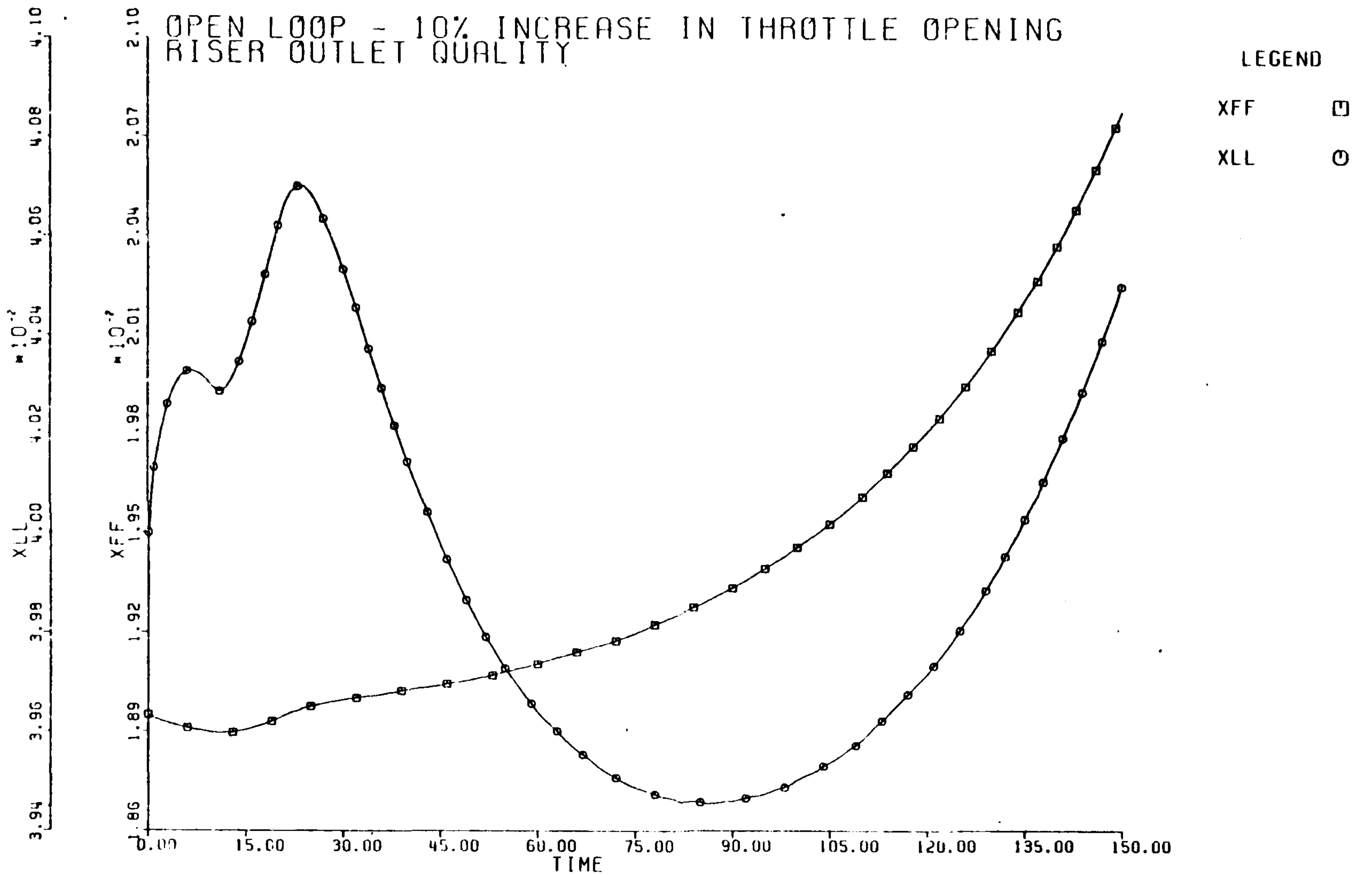
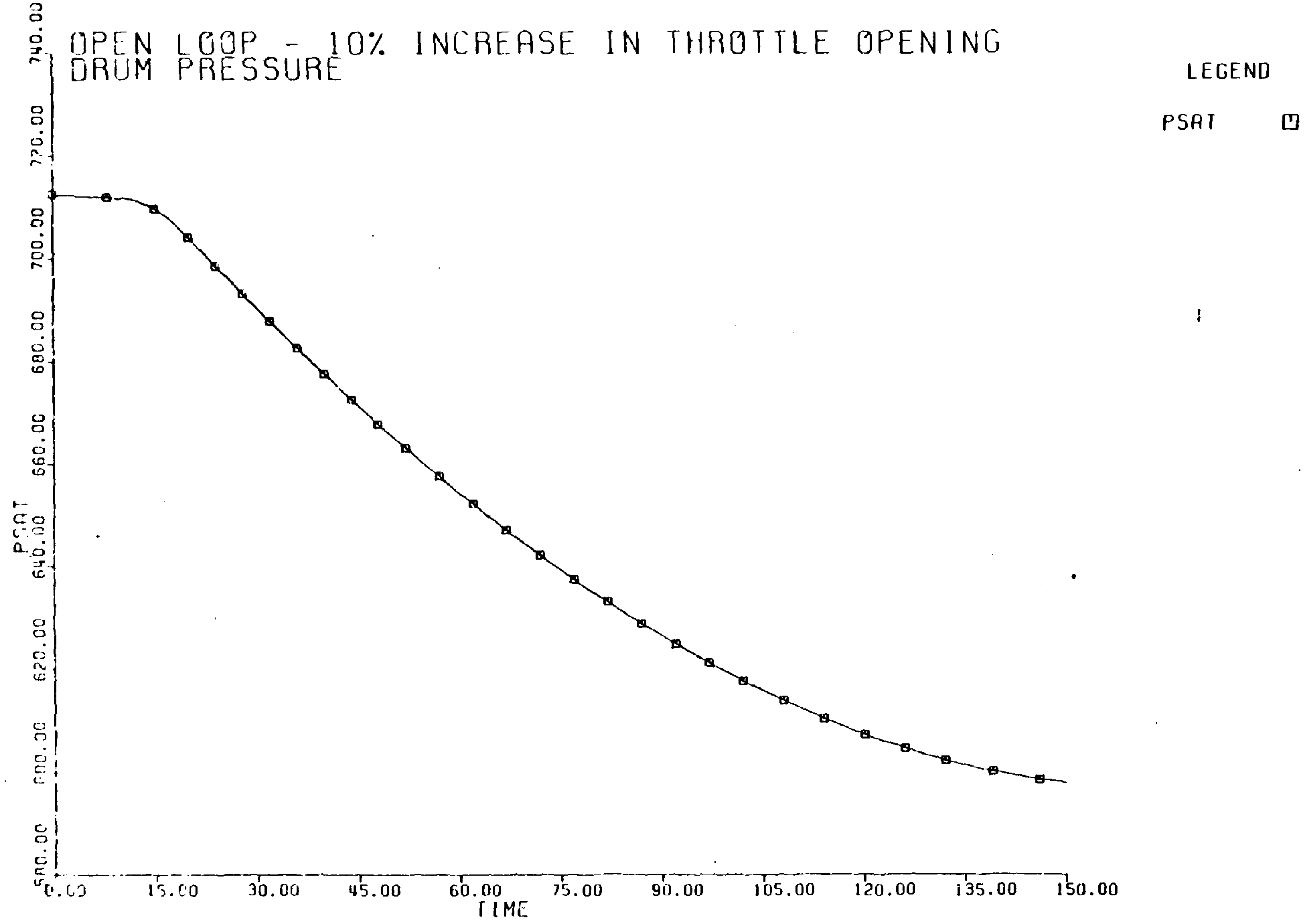

OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
RISER OUTLET QUALITY
LEGEND
XFF
XLL
XLL $\times 10^{-2}$
3.94
3.96
3.98
4.00
4.02
4.04
4.06
4.08
4.10
XFF $\times 10^{-2}$
1.86
1.89
1.92
1.95
1.98
2.01
2.04
2.07
2.10
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 5.



OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
DRUM PRESSURE
LEGEND
PSAT
740.00
720.00
700.00
680.00
660.00
640.00
620.00
600.00
580.00
PSAT
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 6.

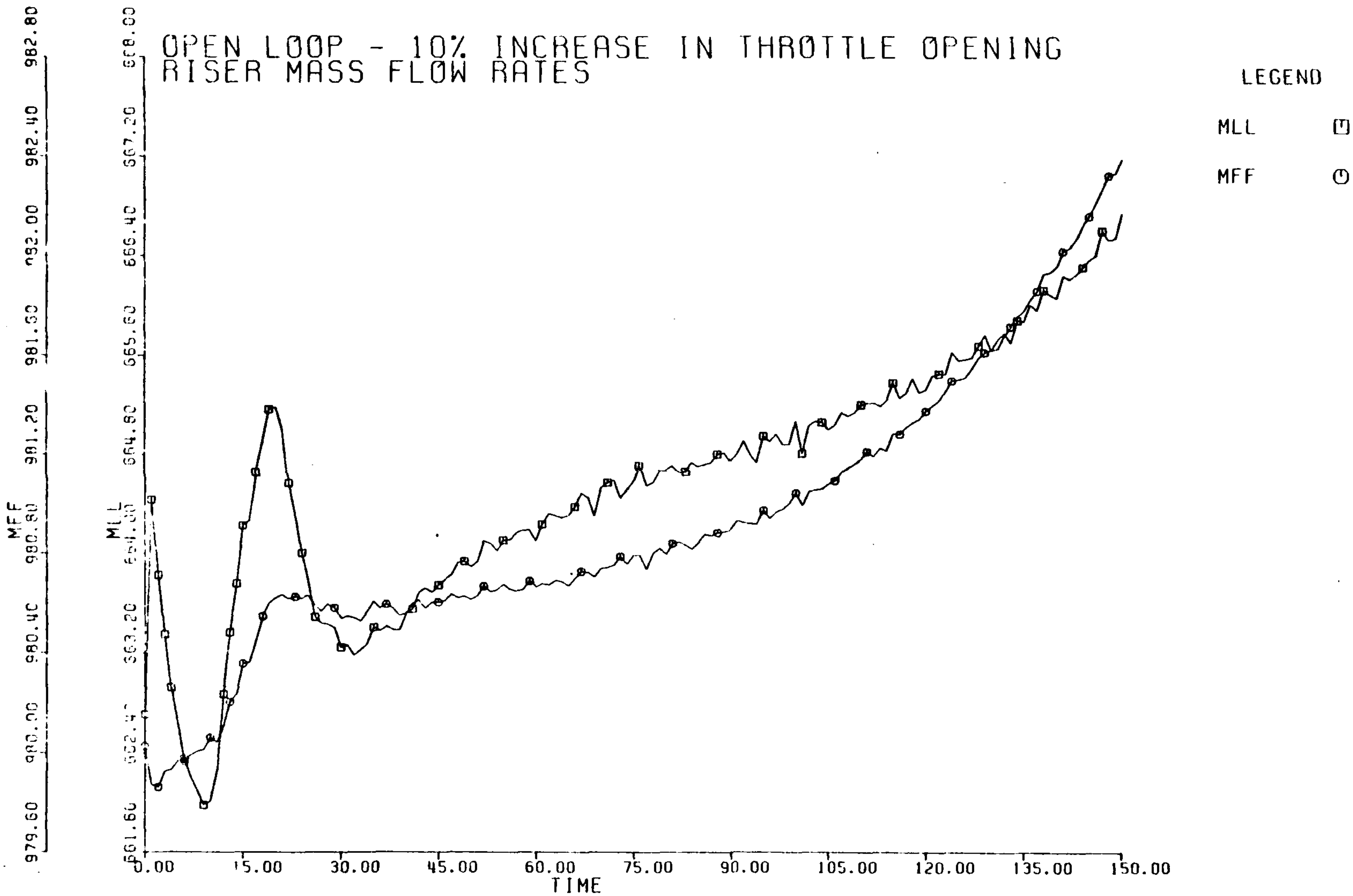

OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
RISER MASS FLOW RATES
LEGEND
MLL
MFF
TIME
MLL
MFF
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
663.20
664.80
665.60
666.40
667.20
979.60
980.40
980.80
981.20
982.40
982.80

Figure 7.

APPENDIX A

```
08/30/79  20.55.11
FILE: CONSTANT FORTRAN  A1                      NAVAL POSTGRADUATE SCHOOL

C       THIS PROGRAM CALCULATES THE CONSTANTS AND INITIAL CONDITIONS
C       FOR A US NAVY D-TYPE BOILER GIVEN THE INPUT DATA OBTAINED FROM
C       THE BOILER TECHNICAL MANUAL, STEAM TABLES, AND STANDARD ENGINEER-
C       ING HANDBOOKS.  THE INPUT DATA ARE ENTERED IN NAME LIST FORMAT.
C       NAMELIST DESIGNATIONS AND INPUT NEMONICS FOLLOW
C
C
C       INCON1:
C
C             OPPNT    OPERATING POINT(PERCENT)   *
C             TOTSTM   TOTAL STEAM FLOW(LB/HR)
C             SPHSTM   SUPERHEATER STEAM FLOW (LB/HR)
C             DSHSTM   DESUPERHEATED STEAM FLOW (LB/HR)
C             PDRUM    DRUM PRESSURE (PSIG)
C             SHOT     SUPERHEATER OUTLET TEMPERATURE (DEG-F)
C             SHOP     SUPERHEATER OUTLET PRESSURE (PSIG)
C             DSHOT    DESUPERHEATER OUTLET TEMPERATURE (DEG-F)
C             DSHOP    DESUPERHEATER OUTLET PRESSURE (PSIG)
C             ECONIT   ECONOMIZER FEED INLET TEMPERATURE (DEG-F)
C             ECONOT   ECONOMIZER FEED OUTLET TEMPERATURE (DEG-F)
C             AIRTMP   AIR INLET TEMPERATURE TO REGISTERS (DEG-F)
C             OILTMP   OIL TEMPERATURE AT BURNER INLET (DEG-F)
C             AIRFLO   AIRFLOW RATE (LB/HR)
C             OILFLO   OIL FLOW RATE (LB/HR)
C             XCSAIR   EXCESS AIR (PERCENT)   *
C             DRAFT    DRAFT LOSS (IN-H2O)
C             TGASSC   FLUE GAS TEMPERATURE LEAVING SCREEN (DEG-F)
C             TGASSH   FLUE GAS TEMPERATURE LEAVING SUPERHEATER (DEG-F)
C             TGASMB   FLUE GAS TEMPERATURE LEAVING MAIN BANK (DEG-F)
C             TGASEC   FLUE GAS TEMPERATURE LEAVING ECONOMIZER (DEG-F)
C             TSCRN    SCREEN TUBE WALL TEMPERATURE (DEG-F)
C             TSPHTR   SUPERHEATER TUBE WALL TEMPERATURE (DEG-F)
C             HRFVOL   HEAT RELEASE (KBTU/HR/CU FT FURNACE VOLUME)
C             FHAS     FURNACE HEAT ABSORBTION (KBTU/HR/SQ FT RADIANT HEAT
C                      ABSORBING AREA)
C
C             NOTE: "PERCENT" VALUES ARE TO BE LOGGED AS DECIMALS.
C
C       $SCREEN
C
C             DTUBSC   AVERAGE INSIDE DIAMETER OF SCREEN TUBES (IN)
C             LAVSC    AVERAGE LENGTH OF SCREEN TUBE (FT)
C             NTUBSC   NUMBER OF SCREEN TUBES
C             RHASSC   RADIANT HEAT ABSORBING AREA OF FURNACE SCREEN (SQ FT)
C             MASSSC   TOTAL WEIGHT OF SCREEN TUBES (LB)
C
C
C       $SPHTR
C
C             AREASH   TOTAL SUPERHEATER HEAT TRANSFER AREA (SQ FT)
C             MASSSH   TOTAL WEIGHT OF SUPERHEATER TUBES
C
C
C       $MNBANK
C
C
C             DTUBMB   AVERAGE INSIDE DIAMETER OF MAIN BANK TUBES (IN)
C             LAVMB    AVERAGE LENGTH OF MAIN BANK TUBE (IN)
C             NTUBMB   NUMBER OG MAIN BANK TUBES
C             MASSMB   TOTAL WEIGHT OG MAIN BANK TUBES (LB)
C             AREAMB   TOTAL HEAT TRANSFER AREA (SQ FT)
C
C
C       $ECON
C
C             DTUBEC   INSIDE DIAMETER OF ECONOMIZER TUBES(IN)
C             NPASSE   NUMBER OF TUBE PASSES
C             NTUBEC   NUMBER OF TUBES PER PASS
C             LTUBEC   AVERAGE LENGTH OF ECONOMIZER TUBE (FT)
C             MASSEC   TOTAL WEIGHT OF ECONOMIZER (LB)
```

```
C
C
C      $DESPH
C
C         DTUBDS   INSIDE DIAMETER OF DESUPERHEATER TUBE (IN)
C         NTUBDS   NUMBER OF DESUPERHEATER TUBES PER PASS
C         NPASSD   NUMBER OF DESUPERHEATER TUBE PASSES
C         LTUBDS   LENGTH OF DESUPERHEATER TUBE (FT)
C         AREADS   TOTAL HEAT TRANSFER AREA OF DESUPERHEATER (SQ FT)
C         MASSDS   TOTAL WEIGHT OF DESUPERHEATER ASSEMBLY (LB)
C
C
C      $DRMDCR
C
C         DTUBDD   AVERAGE DIAMETER OF DRUM DOWNCOMER TUBES (IN)
C         LAVDC    AVERAGE LENGTH OF DRUM DOWNCOMER TUBE (FT)
C         NTUBDC   NUMBER OF DRUM DOWNCOMER TUBES
C
C
C      $HDRDCR
C
C         DTUBHC   AVERAGE INSIDE DIAMETER OF HEADER DOWNCOMER (IN)
C         LAVHD    AVERAGE LENGTH OF HEADER DOWNCOMER (FT)
C         NTUBHD   NUMBER OF HEADER DOWNCOMERS
C
C
C      $BOILER
C
C         DSTMDM   DIAMETER OF STEAM DRUM (IN)
C         LSTMDM   LENGTH OF STEAM DRUM (FT)
C         DWTRDM   DIAMETER OF WATER DRUM (IN)
C         LWTRDM   LENGTH OF WATER DRUM (FT)
C         HNORM    HEIGHT OF NORMAL WATER LEVEL ABOVE BENCH MARK (FT)
C         HHDR     HEIGHT OF HEADER (SCREEN) ABOVE BENCH MARK (FT)
C         HWTRDM   HEIGHT OF WATER DRUM ABOVE BENCH MARK (FT)
C         FURVOL   FURNACE VOLUME (CU FT)
C
C         NOTE:  CHOICE OF BENCH MARK IS ARBITRARY
C
C      $THERMO
C
C         HSHOUT   ECONOMIZER OUTLET ENTHALPY (BTU/LBM)
C         HDSOUT   DESUPERHEATER OUTLET ENTHALPY (BTU/LBM)
C         HECIN    ENTHALPY OF ECONOMIZER FEED INLET (BTU/LBM)
C         HECOUT   ENTHALPY OF ECONOMIZER FEED OUTLET (BTU/LBM)
C      (1)KH2O     THERMAL CONDUCTIVITY OF WATER  (BTU/HR.FT.DEG-F)
C      (1)PRH2O    PRANDTL NUMBER FOR WATER
C      (1)VSCH2O   KINEMATIC VISCOSITY FOR WATER (LBM/FT-SEC)
C      (2)KSTM     THERMAL CONDUCTIVITY FOR STEAM (BTU/HR.FT.DEG-F)
C      (2)PRSTM    PRANDTL NUMBER FOR STEAM
C      (2)VSCSTM   KINEMATIC VISCOSITY FOR STEAM (LBM/FT-SEC)
C         RSHOUT   SUPERHEATER OUTLET DENSITY (LBM/CU FT)
C         RDSOUT   DESUPERHEATER OUTLET DENSITY (LBM/CU FT)
C         RFLUE    DENSITY OF FLUE GAS AT TGASSC (LBM/CU FT)
C
C         NOTES:   (1) EVALUATED AT AVERAGE ECONOMIZER WATER TEMPERATURE
C                  (2) EVALUATED AT AVERAGE DESUPERHEATER STEAM TEMPERATUR
C
C      $LOSSES
C         KSDSC    ROUGHNESS RATION (SAND EQUIVALENT) FOR SCREEN TUBES
C         KSDMB    ROUGHNESS RATIO (SAND EQUIVALENT) OF MAIN BANK TUBE
C         KSDDC    ROUGHNESS RATIO (SAND EQUIVALENT) FOR DRUM DOWNCOMER
C         KSDHD    ROUGHNESS RATIO (SAND EQUIVALENT) FOR HEADER DOWNCOMER
C         ENTSC    SCREEN TUBE ENTRANCE LOSS
C         BENDSC    SCREEN TUBE BEND LOSS
C         ENTMB    MAIN BANK ENTRANCE LOSS
C         BENDMB   MAIN BANK BEND LOSS FACTOR
C         ENTDD    DRUM DOWNCOMER ENTRANCE LOSS FACTOR
C         BENDDD   DRUM DOWNCOMER BEND LOSS FACTOR
C         ENTHD    HEADER DOWNCOMER ENTRANCE LOSS FACTOR
```

```
C          BENDHD  HEADER DOWNCOMER BEND LOSS FACTOR
C
      IMPLICIT REAL(A-Z)
      INTEGER NPASSE
      DIMENSION TH2O(20),OPASS(20)
C
C     DEFINE NAMELISTS
C
      NAMELIST/INCON0/CFPNT,TOTSTM,SPHSTM,DSHSTM,PORUM,SHOT,SHOP,DSHOT,
     1DSHOP,ECOIIT,ECONOT,AIRTMP,OILFLO,AIRFLC,XCSAIR,DRAFT,TGASSC,
     2TGASSH,TGASMB,TGASEC,TSCRN,TSPHTR,HRFVOL,FHAS,OILTMP
      NAMELIST/SCREEN/DTUBSC,LAVSC,NTUBSC,FHASSC,MASSSC
      NAMELIST/SPHTR/AREASH,MASSSH
      NAMELIST/MNBANK/DTUBMB,LAVMB,NTUBMB,MASSMB,AREAMB
      NAMELIST/ECON/DTUBEC,NPASSE,NTUBEC,LTUBEC,MASSEC
      NAMELIST/DESPH/DTUBDS,NTUBDS,NPASSD,LTUBDS,AREADS,MASSDS
      NAMELIST/DRMDCR/DTUBDD,LAVDD,NTUBDD
      NAMELIST/HDRDCR/DTUBHD,LAVHD,NTUBHD
      NAMELIST/BOILER/DSTMDM,LSTMDM,DWTRDM,LWTRDM,HNORM,HHOR,HWTRDM,
     $FURVOL
      NAMELIST/THERMO/HSHOUT,HDSOUT,HECIN,HECOUT,
     1KH2O,PRH2O,VSCH2O,KSTM,PRSTM,VSCSTM,RSHOUT,RDSOUT,RFLUE
      NAMELIST/LOSSES/KSDSC,KSDMB,KSDDD,KSDHD,ENTSC,BENDSC,ENTMB,
     $BENDMB,EXITDD,BENDDD,ENTHD,BENDHD
      NAMELIST/INCON1/TRRO,TVVO,TWWO,
     &TYYC,TZZC,TXXO,TAAO
      NAMELIST/INCON2/MAAO,MFQQO,MAOQO,
     &MNNO,MMMO,MQQO,
     &MCDO,MGHO,MBBO,
     &MFFO,MLLO,MME,
     &MASSV,MASSW,MASSY,
     &MASSX,MASSZ,MASSQR,
     &DMDHIC,DMASLO,DSTMO,CSTMDM,
     &LSTMDM,DSTMDM
      NAMELIST/INCON3/CMN,CAB,CPV,
     &CPY,CPX,CPZ,
     &CPW,CQR,CRS,CST,
     &CTU,CNF,G,GC
      NAMELIST/CONST1/KSJL,KSDF,KSGH,
     &KSCC,KSDE,KSEF,
     &KSJK,KSKL,KZ,
     &KW,KRS,KST,
     &KON1,KON3,KON4,
     &KX,KHJ,KV,
     &KTU,KY
      NAMELIST/CONST2/AJL,CJL,LJL2,
     &LJL1,DDF,LDF,
     &LCF1,ACF,LGH,
     &AGH,CGH,DCD,
     &LCD,LDEO,LJKO
      NAMELIST/CONST3/ACD,ZBENC1,ZBENC2,
     &VOLJL,VCLDF,VCLDHM,
     &VOLHJ,ZDF,ZJL,
     &LJL,DDF,DKL,
     &CEF,DJK,ZCD
      NAMELIST/CONST4/FCD,FGH,FDE,
     &FEF,FJK,FKL,
     *ENTRGH,EXITCD,BENDGH,
     &BENDCD,EXITGH,EXITCD
      NAMELIST/CONST5/FHV,XLLO,XFFO,
     &TAMB,DRDCFO,DRDJLO,
     &SIGMAA
      NAMELIST/OUTPUT/Q10,Q40,Q60,Q80,Q90,MFFO,MLLO,CCO,
     &XFFO,XLLO,RHCDFO,RHDJLO,RHDFFO,RHOLLO,
     &HSAT,HCDC,HAAO,HBBO,HJJO,HFG,RHCF,DMDVO,HXFFO,HXLLO
C
      READ(5,INCON0)
      READ(5,SCREEN)
      READ(5,SPHTR)
      READ(5,MNBANK)
```

```
      READ(5,ECON)
      READ(5,DESPH)
      READ(5,DEMDCR)
      READ(5,HDRDCR)
      READ(5,BOILER)
      READ(5,THERMO)
      READ(5,LOSSES)
C     CALCULATION OF PRELIMINARY CONSTANTS
C
      PI=3.1415927
      G=32.2
      PRAA=PRH2O
      VISCOA=VSCH2O
      THCONA=KH2O
      PRAN=PRSTM
      VISCON=VSCSTM
      THCONN=KSTM
      XASUME=0.05
      FCL=.015
      GC=32.2
      VALVEO=OPPNT
      KSCD=KSDHD
      KSDF=KSDSC
      KSDE=KSDF
      KSEF=KSDF
      CM=.11
      CPV=CM
      CPY=CM
      CPX=CM
      CPZ=CM
      CPW=CM
      KSGH=KSDCD
      KSJL=KSDMB
      KSJK=KSJL
      KSKL=KSJL
      ENTRCD=ENTHD
      ENTRGH=ENTDC
      BENDCD=BENDHD
      BENDGH=BENDMB
      EXITCD=1.0
      EXITGH=1.0
      PSAT=PDRUM+14.7
      HSAT=EXP(0.26452*ALOG(PSAT)+4.46708)
      HFG=922.15-0.40516*PSAT+1.717E-04*PSAT**2.0-4.219E-08*PSAT**3.0
      HV=HSAT+HFG
      HMMO=HV
      HF=HSAT
      TSAT=EXP(.22151*ALOG(PSAT)+4.77123)
      MFCQO=OILFLO/3600.0
      MACCO=AIRFLO/3600.0
      TRRO=TGASSC
      TVVO=TSCRN
      TWWO=TSPHTR
      TQRO=TRRO
      TSSO=TGASSH
      TMMO=TSAT
      TTTO=TGASMB
      TUUO=TGASEC
      TTLG=(TTTO+TUUO)/2.0
      TAMB=80.0
      MMMO=TOTSTM/3600.0
      MMME=MMMO*.0001
      MMMIII=SPHSTM/3600.0
      TNNO=SHOT
      TPPC=DSHOT
      PNNO=SHOP+14.7
      FMMO=FORLM
      MMMII=DSHSTM/3600.0
      MNNO=MMMII
      TAAO=ECONIT
```

```
      TBBO=ECONOUT
      VBBO=.01600488-.0000020146*TBBO+.00000003651l*TBBO**2.0
     &-8.142E-11*TBBO**3.0+1.4081E-13*TBBO**4.0-1.148E-16*
     &TBBO**5.0+8.034E-20*TBBO**6.0
      CTCTO=HRFVCL*1000.0/3600.0
      HNNO=HSHOUT
      CFURAB=FFAS*1000.0/3600.0
      ARAC=RHASSC
      HPPC=HDSOUT
      LCF1=LAVSC
      LOF2=LDEL*NTUBSC
      CDF=DTUBSC*NTUBSC/12.0
      CDE=CDF
      DEF=DDE
      ACF=PI*DTUBSC**2.0*NTUBSC/(4.0*144.0)
      VOLDF=ACF*LDF1
      MASSV=MASSSC
      MASSW=MASSSH
      LJL1=LAVMB
      LJL2=NTUBMB*LJL1
      DJL=DTUBMB*NTUBMB/12.0
      DJK=DJL
      CKL=DJK
      AJL=PI*DTUBMB**2.0*NTUBMB/(4.0*144.0)
      VOLJL=AJL*LJL1
      MASSY=MASSMB
      MASSX=MASSEC
      MASSZ=MASSDS
      ZBENC1=HDRUM-HHDR
      LDF=ZBENC1
      ZDF=ZBENC1
      ZBENC2=HNDRUM-HWTROM
      LJL=ZBENC2
      ZJL=ZBENC2
      ZCD=ZCF
      ZGH=ZJL
      DRODFO=0.0
      DRDJLO=0.0
      LAB=LTUBEC
      DAB=DTUBEC/12.0
      AREAEC=NTUBEC*LAB*PI*DAB*NPASSE
      DNP=DTUBDS/12.0
      LCD=LAVHD*NTUBHD
      LGH=LAVDD*NTUBDD
      DCD=DTUBHD*NTUBHD/12.0
      DGH=DTUBDD*NTUBDD/12.0
      ACD=NTUBHD*(PI*(DTUBHD/24.0)**2.0)
      AGH=NTUBDD*(PI*(DTUBDD/24.0)**2.0)
      VOLDFM=(PI*DSTMDM**2.0/(4.0*144.0))*LSTMDM
      VOLHJ=(PI*DWTRDM**2.0/(4.0*144))*LWTRDM
      HAAO=HECIN
      HBBO=HECOUT
      RHOF=63.8-0.01781*TSAT+1.132E-05*TSAT**2.0-6.786E-08*TSAT**3.0
      VF=1.0/RHOF
      VFG=524.0/PSAT-0.1
      VV=VF+VFG
      RHOV=1.0/VV
      RHOFG=RHOF-RHOV
      RHOMMO=RHOV
      RHONNO=RSHOUT
      RHOPPO=RDSOUT
      MAAO=MNNO
      MBBO=MAAO
C
C          CALCULATE THE TOTAL MASS OF FLUE GAS IN THE FURNACE
C
      MASSCR=RFLUE*FURVOL
C
C          CALCULATE THE TOTAL ENERGY ENTERING BOILER
C
```

```
      QQC=QTOTC*FURVOL
C
C          CALCULATE "LUMPED" LOWER HEATING VALUE OF FUEL/AIR MIX
C
      FHV=QQQ/MFQQO
C
C          CALCULATE ENERGY ABSORBED BY RADIATION IN FURNACE-C
C
      Q10=CFLFAB*ARAD
C
      Q20=Q10
C
C          CALCULATE THE STEFAN-BOLTZMAN CONSTANT MULTIPLIED BY THE
C          SCREEN AREA
C
      SIGMAA=Q10/((TQRC+460.0)**4.0-(TVVO+460.0)**4.0)
C
C          CALCULATE THE TOTAL FLUE GAS MASS FLOW RATE INTO BOILER
C
      MQQO=MFQQO+MAQQO
      MRRO=MQQO
      MSSO=MRRO
      MTTO=MSSO
      MUUO=MTTO
C
C          COMPUTE THE ENERGY TRANSFERRED TO THE WATER (LOWER) DRUM
C          BY THE DESUPERHEATER
C
      Q90=MNNO*(HNNO-HPPO)
      Q990=Q90
C
C          CALCULATE THE ENERGY TRANSFERRED TO THE MAIN BANK RISERS
C
      Q60=MMMO*(HMMO-HEEO)-Q20-Q990
      Q50=Q60
C
C          COMPUTE THE MAIN BANK HEAT TRANSFER COEFFICIENT-TUBE METAL
C          TO STEAM SIDES
C
      KY=AREAMB/1.782E06
C
C          COMPUTE THE MAIN BANK TUBE METAL TEMPERATURE
C
      TYYO=(Q60/(KY*PSAT**(4.0/3.0)))**(1.0/3.0)+TSAT
C
C          COMPUTE THE MAIN BANK HEAT TRANSFER COEFFICIENT-FLUE GAS
C          TO TUBE METAL
C
       TSTO=(TSSO+TTTO)/2.0
       KST=Q50/(MSSO**0.6*(TSTO-TYYO))
C
C          COMPUTE THE SCREEN BANK HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO STEAM SIDES
C
      KV=Q10/(PSAT**(4.0/3.0)*(TVVO-TSAT)**3.0)
C
C          COMPUTE THE HEAT TRANSFER TO THE SUPERHEATER
C
      Q40=MMMO*(HNNO-HMMO)
      Q30=Q40
C
C          COMPUTE THE SPECIFIC HEAT OF THE STEAM
C          IN THE SUPERHEATER
C
      CMN=Q40/(MMMO*(TNNO-TMMO))
C
C          COMPUTE THE SUPERHEATER HEAT TRANSFER COEFFICIENT-FLUE
C          GAS TO TUBE METAL-C
C
      TRSO=(TRRO+TSSO)/2.0
```

```
      KRS=Q30/(MRRO**0.6*(TRSO-TWWO))
C
C          COMPUTE THE HEAT TRANSFER TO THE ECONOMIZER
C
      Q8C=MAAO*(HBBO-HAAO)
      Q7C=Q80
C
C          COMPUTE THE SPECIFIC HEAT OF THE FEEDWATER
C          IN THE ECONOMIZER
C
      CAB=Q8C/(MAAO*(TBBO-TAAO))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE FURNACE
C
      CQR=(Q00-Q1O)/(MRRO*(TQRO-TAMB))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE SUPERHEATER
C
      CRS=Q30/(MRRO*(TRRO-TSSO))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE MAIN BANK
C
      CST=Q50/(MSSO*(TSSO-TTTO))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE ECONOMIZER
C
      CTU=Q70/(MTTO*(TTTO-TUUO))
C
C          COMPUTE THE ECONOMIZER HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO LIQUID
C
      KX=((.023*THCONA)/DAB)*(4.0/(PI*DAB*VISCOA*NTUBEC))**0.8
     &*PRAA**0.4*AREAEC
C
C          COMPUTE THE LMTD FOR THE ECONOMIZER
C
      LMTDAB=Q80/(KX*MAAO**0.8)
C
C          COMPUTE THE ECONOMIZER TUBE METAL TEMPERATURE
C
      EXPOEC=EXP((TBBO-TAAO)/LMTDAB)
      TXXO=(TAAO-TBBO*EXPOEC)/(1.0-EXPOEC)
C
C          COMPUTE THE ECONOMIZER HEAT TRANSFER COEFFICIENT-FLUE
C          GAS TO TUBE METAL
C
      KTU=Q70/(MTTO*(TTUO-TXXO))
C
C          COMPUTE THE DESUPERHEATER HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO STEAM
C
      KZ=((.023*THCONN)/DNP)*(4.0/(PI*DNP*VISCON*NTUBDS))
     &**0.8*PRAN**0.3*AREADS
C
C          COMPUTE THE DESUPERHEATER LMTD
C
      LMTDNP=Q90/(KZ*MNNO**0.8)
C
C          COMPUTE THE SPECIFIC HEAT OF STEAM IN THE DESUPERHEATER
C
      CNP=Q90/(MNNO*(TNNO-TPPO))
C
C          COMPUTE DESUPERHEATER TUBE METAL TEMPERATURE
C
      EXPODS=EXP((TNNO-TPPO)/LMTDNP)
      TZZO=(TNNO-EXPODS*TPPO)/(1.0-EXPODS)
C
C          COMPUTE THE DESUPERHEATER HEAT TRANSFER COEFFICIENT-
C          WATER DRUM LIQUID TO TUBE METAL
C
```

```
      KHJ=Q99C/(TZZC-TSAT)
C
C          COMPUTE THE SUPERHEATER LMTD
C
      LMTDMN=(TNNO-TMMO)/(ALOG((TWWO-TMMO)/(TWWO-TNNO)))
C
C          CALCULATE THE SUPERHEATER HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO STEAM
C
      KW=Q40/(MMMO**0.8*LMTDMN)
C
C          CALCULATE THE THROTTLE VALVE FLOW COEFFICIENT
C
      KON4=MMMIII/(VALVEO*PNNO)
C
C          CALCULATE THE SUPERHEATER OUTLET DENSITY
C
      KON3=(PMMO+PNNO)/(RHOMMO+RHONNO)
      RHONNO=(RHOMMO+RHONNO)/2.0
      KON1=((PMMO-PNNO)*RHOMNO)/MMMO**2.0
C
C          COMPUTE THE FRICTION FACTORS FOR THE DOWNCOMERS
C          AND THE RISERS
C
      FCD=1.0/(1.74-2.0*ALOG10(KSCD))
      FGH=1.0/(1.74-2.0*ALOG10(KSGH))
      FDE=1.0/(1.74-2.0*ALOG10(KSDE))
      FEF=1.0/(1.74-2.0*ALOG10(KSEF))
      FJK=1.0/(1.74-2.0*ALOG10(KSJK))
      FKL=1.0/(1.74-2.0*ALOG10(KSKL))
C-----------------------------------------------------------------------
C
C          START ITERATION TO BALANCE CIRCULATION LOOPS
C
C
C-----------------------------------------------------------------------
C
C          COMPUTE INITIAL VALUE OF RISER OUTLET MASS FLOW RATE
C
      MFFO=Q10/(XASUME*HFG)
      MLLO=Q50/(XASUME*HFG)
C
C          CALCULATE THE INITIAL DOWNCOMER ENTHALPY
C
   71 HCDO=((MFFO+MLLO-MBBO)*HF+MBBO*HBBO+0.0*(MFFO+MLLO)
     &*HV)/(MFFO+MLLO)
      HGHO=HCDO
C
C          COMPUTE THE INITIAL DRUM ENTHALPY
C
      HDRUMO=HCDO
C
C          COMPUTE MAIN BANK RISER INLET ENTHALPY
C
      MHHO=MLLO
      HJJO=HGHO+Q90/MHHO
C
C          CALCULATE THE RISER INLET DENSITY
C
      RHODDO=RHOF
      RHOJJO=RHOF
C
C          COMPUTE THE DOWNCOMER DENSITY
C
      VCDO=((MFFO+MLLO-MBBO)*VF+MBBO*VBBO)
     &/(MFFO+MLLO)
      RHOCDO=1.0/VCDO
      RHOGHO=RHOCDO
C
C          CALCULATE THE RISER OUTLET QUALITY
C
```

```
      HDDO=HCDO
      XFFO=(Q1C+MFFO*(HF-HCDO))/(MFFO*HFG)
      XLLO=(Q5O+MLLO*(HF-HJJO))/(MLLO*HFG)
C
C        CALCULATE THE RISER OUTLET DENSITY
C
      RHOFFO=RHOF-XFFO*RHOFG
      RHOLLO=RHOF-XLLO*RHOFG
C
C        CALCULATE THE NONBOILING LENGTH OF THE RISERS
C
      ZBENC1=HNORM-HHCR
      LDF=ZBENC1
      LDEO=LDF*AMAX1((HF-HDDO),0.0)/((HDDO+XFFO*HFG)-HDDO)
      ZBENC2=HNORM-HWTRCM
      LJL=ZBENC2
      LJKO=LJL*AMAX1((HF-HJJO),0.0)/((HJJO+XLLO*HFG)-HJJO)
C
C        CALCULATE BOILING LENGTH OF RISERS
C
      LEFO=LDF-LDEO
      LKLO=LJL-LJKO
C
C        CALCULATE THE AVERAGE DENSITY IN THE SCREEN RISER
C
      RHODFO=(1.0/LDF)*(LEFO/((XFFO)*VFG)*ALOG(((XFFO
     &)/VF)*VFG+1.0)+RHODDO*LDEO)
C
C        CALCULATE THE AVERAGE DENSITY IN THE MAIN BANK RISER
C
      RHOJLO=(1.0/LJL)*(LKLO/((XLLO)*VFG)*ALOG((XLLO
     &*VFG)/VF+1.0)+RHOJJO*LJKO)
C
C        CALCULATE THE EFFECTIVE HEIGHT OF THE RISERS
C
      ZDEO=ZDF-LEFO
      ZJKO=ZJL-LKLO
      ZEFO=ZDF-ZDEO
      ZKLO=ZJL-ZJKO
C
C        COMPUTE THE TWO PHASE FLOW MULTIPLICATION FACTORS
C
      RGRAVE=24.794*XFFO**2.0-6.5066*XFFO+.9776
      RGRAVK=24.794*XLLO**2.0-6.5066*XLLO+.9776
      RACLE=15.4564*XFFO**2.0+13.4944*XFFO-.00007
      RACLJ=15.4564*XLLO**2.0+13.4944*XLLO-.00007
      RFRICE=-34.0822*XFFO**2.0+23.7164*XFFO+.8734
      RFRICK=-34.0822*XLLO**2.0+23.7164*XLLO+.8734
C
C        CALCULATE SECOND APPROXIMATION OF MASS FLOW RATE AT
C        EXIT OF SCREEN RISERSM
C
      RHOEEO=RHODDO
      MFFOO=((RHOCDO*G*ZCD-G*ZDEO*((RHODDO+RHOEEO)/2.0)
     &-G*ZEFO*RHOEEO*RGRAVE)/((FCD*LCD/DCD+ENTRCD
     &+BENDCD+EXITCD)/(2.0*ACD**2.0*RHOCDO)+((RHOEEO-RHODDO)
     &/(RHOEEO*RHODDO*ADF**2.0))+(4.0*FDE*LDEO*2.0
     &)/(2.0*DDF*(RHOEEO+RHODDO)*ADF**2.0)+RACLE/
     &(RHOEEO*ADF**2.0)+(4.0*FEF*LEFO*RFRICE)/
     &(2.0*DDF*RHOEEO*ADF**2.0)))**0.5
C
C        CALCULATE SECOND APPROXIMATION OF MASS FLOW RATE
C        AT EXIT OF MAIN BANK RISERS
C
      RHOKKO=RHOJJO
      MLLOO=((RHOGHO*G*ZGH-G*ZJKO*((RHOJJO+RHOKKO)/2.0)
     &-G*ZKLO*RHOKKO*RGRAVK)/((FGH*LGH/DGH+ENTRGH
     &+BENDGH+EXITGH)/(2.0*AGH**2.0*RHOGHO)+((RHOKKO-RHOJJO)
     &/(RHOKKO*RHOJJO*AJL**2.0))+(4.0*FJK*LJKO*2.0
     &)/(2.0*DJL*(RHOKKO+RHOJJO)*AJL**2.0)+RACLJ/
```

```
     &(RHOKKC*AJL**2.0)+(4.0*FKL*LKLO*RFRICK)/
     &(2.0*DJK*RHOKKO*AJL**2.0)))**0.5
C
C          COMPARE PREVIOUS APPROXIMATION FOR  RISER MASS
C          FLOW RATE TO CURRENT, IF WITHIN ERROR CRITERIA CONTINUE,
C          IF NOT, UPDATE AND THEN REITERATE-
C
      CHECK=0.0
      IF(ABS(MFFO-MFFOO).LT..01)GO TO 62
      MFFO=(MFFOO-MFFO)/2.0+MFFO
      CHECK=1.0
   62 IF(ABS(MLLO-MLLOO).LT..01)GO TO 64
      MLLO=(MLLOO-MLLO)/2.0+MLLO
      GO TO 71
   64 IF(CHECK.EQ.1.0)GO TO 71
C
C          COMPUTE INITIAL MASS OF LIQUID IN DRUM
C
      DMASLO=(VOLDRM*RHOCDO)/2.0
C
C          COMPUTE THE INITIAL DRUM "LIQUID" VOLUME
C
      DMDVC=VOLDRM/2.0
C
C          COMPUTE THE INITIAL ENERGY STORED IN DRUM LIQUID
C
      DMCHLO=DMASLO*HDRUMO
C
C          EQUATE INITIAL FLOW RATES
C
      MCDO=MFFO
      MGHO=MLLO
C
C          COMPUTE INITIAL MASS OF STEAM IN STEAM
C          DRUM
C
      DSTMO=VOLDRM*RHOV/2.0
C
C          COMPUTE HXFFO AND HXLLO
C
      HXFFO=HF+HFG*XFFO/2.0
      HXLLO=HF+HFG*XLLO/2.0
C
      WRITE(6,600)
  600 FORMAT(1H1)
      WRITE(6,INCON1)
      WRITE(6,601)
  601 FORMAT(1H0)
      WRITE(6,INCON2)
      WRITE(6,601)
      WRITE(6,INCON3)
      WRITE(6,601)
      WRITE(6,CONST1)
      WRITE(6,601)
      WRITE(6,CONST2)
      WRITE(6,601)
      WRITE(6,CONST3)
      WRITE(6,601)
      WRITE(6,CONST4)
      WRITE(6,601)
      WRITE(6,CONST5)
      WRITE(6,601)
      WRITE(6,600)
      WRITE(6,OUTPUT)
      WRITE(7,INCON1)
      WRITE(7,INCON2)
      WRITE(7,INCON3)
      WRITE(7,CONST1)
      WRITE(7,CONST2)
      WRITE(7,CONST3)
```

```
      WRITE(7,CONST4)                                                   CON07010
      WRITE(7,CONST5)                                                   CON07020
      WRITE(7,OUTPUT)                                                   CON07030
      STOP                                                              CON07040
      END                                                               CON07050
```

A P P E N D I X   B

```
06/30/79  21.26.19

FILE: CSMP      FORTRAN  P1                          NAVAL POSTGRADUATE SCHOOL

//HOPEFULL JOB (2473,C567,NE81,,9),'WALKER SMC 1319',TIME=2
//   EXEC CSMPXV
//X.SYSIN  DD  *
*****************************************************************
*
*
*
*****************************************************************
*
*           THIS D TYPE BOILER MODEL IS WRITTEN IN CSMP-III
*           COMPUTER LANGUAGE.  IT IS A NONLINEAR MODEL
*           WHICH UTILIZES A SET OF INITIAL CONDITIONS AND
*           OTHER DATA PREPARED BY AN INITIAL CONDITION FORTRAN
*           MODEL WHICH PRECEDES THIS ONE.  THE MODEL IS GOOD
*           FOR SMALL TRANSIENTS AROUND THE OPERATING POINT
*           SPECIFIED BY THE INITIAL CONDITION PROGRAM.
*
*****************************************************************
INITIAL
CONST DRA41=0.0,DRA42=0.0,DRA43=0.0,DRA44=0.0,DRA45=0.0,DRA46=0.0,...
DRA47=0.0,DRA48=0.0,DRA31=0.0,DRA32=0.0,DRA33=0.0,DRA34=0.0,...
DRA35=0.0,DRA36=0.0,DRA37=0.0,DRA38=0.0
 CONST ONE=1.0, ...
 TRRO=  2563.0000     ,TVVO=  600.00000     ,TWWO=  1033.0000     ,TYYO=...
   515.42749      ,TZZO=  600.99976     ,TXXO=  360.36450
 CONST TWO=2.0, ...
 DMJHO=  2754667.0     ,DMASSO=  5415.8164     ,MAAO=  45.000000 ,TAAO=...
   254.00000      ,MFOOO=  3.3074999      ,MAQOO=  55.398380     ,MNNO=...
   7.7500000      ,MMMO=  45.000000      ,VALVEO= 0.50999999     ,MOOO=...
   59.206375      ,CMN= 0.65523028      ,CAB=  1.0761900,CPV=0.10999995,...
 CPY= 0.10999995     ,CPX= 0.10999995     ,CPZ= 0.10999995     ,CPW=     ...
  0.10999995,DMJHLO=3961626.0,DMASLO=8002.2000,DMOVO=163.65698
 CONST THREE=3.0, ...
 DRODFO= 0.0                ,DFOJLO= 0.0              ,MMME= 0.44999979E-02,...
                   MGHO=  662.70825     ,MBBO=  45.000000     ,LSTMDM=     ...
   16.666666      ,DSTMDM=  60.000000     ,MCDO=980.02734,DLEVO=163.66
 CONST FOUR=4.0, ...
 KSJL= 0.59999991E-04,KSDF= 0.29999996E-04,KSGH= 0.49999999E-05,KSCD=...
  0.49999999E-05,KSDE= 0.29999996E-04,KSEF= 0.29999996E-04,  ...
KSJK=0.59999791E-04, ...
 KSKL= 0.59999991E-04,AJL=  10.678426     ,DJL=  196.57166     ,LJL2=...
   28420.000      ,LJL1=  10.000000     ,DDF=  35.897476,LDF=15.750000,...
 LDF1=  12.700000     ,ADF=  4.0646048     ,LGH=  25.000000     ,AGH=...
   1.4451332,SAMPL=250,RISTIM=10.0
 CONST FIVE=5.0, ...
 DGH=  1.9183321      ,DCD=  4.6699991      ,LCD=  94.500000     ,LDEO=    ...
   2.6166515      ,LJKO= 0.60500102     ,ACD=  2.9547773,MASSV=7951.3984...
,MASSW=  10752.000     ,MASSY=  28192.000     ,MASSX=  24443.000,MASSZ=...
   1617.0000      ,ZBENC1=  15.750000     ,FCD= 0.81023693E-01, ...
 FDE= 0.92714846E-01,FEF= 0.92714846E-01,FGH=0.81023693E-01
 CONST SIX=6.0, ...
 ZBENC2=  12.410001     ,MASSDR= 71.395              ,VOLJL=  106.78426,VCLD...
F= 51.620468      ,VOLDRM=  327.31396     ,VOLHJ=  98.174744
 CONST SEVEN=7.0, ...
 COP= 0.31599814     ,CFS= 0.30453670     ,CST= 0.29042804     ,CTU=     ...
  0.26026064      ,CMP= 0.53347189     ,KNP=  18.508820     ,KW=2.0997724,...
 SIGMAA= 0.21132812E-09,KRS= 0.87199436      ,KST=  2.2037563
 CONST EIGHT=8.0, ...
 KTU= 0.44126600      ,ENTRGH= 0.99999964E-01,ENTRCD= 0.99999964E-01,...
                   BENDCD= 0.99999964E-01,EXITGH=  1.0000000,EXITCD=...
   1.0000000      ,HAAO=  221.00000     ,KOM1= 0.10645876E-01,...
 KOM4= .10777515      ,FJK= 0.98190149E-01,FKL= 0.98190149E-01,...
 GC=  32.199997     ,TAMB=  80.000000      ,ZCD=  15.750000     ,ZDF=     ...
   15.750000      ,ZJL=  12.410001     ,LJL=  12.410001     ,...
BENDGH=0.14999998,KON3=647.71460,G=32.199997,DSTMD=249.59802
 CONST NINE=9.0, ...
 KX=  10.077373      ,KZ=  14.930669     ,KV= 0.32769613E-05,...
 FHV=  19300.496     ,DFE=  35.897476     ,DKL=  196.57166     ,DEF=...
   35.897476      ,DJK=  196.57166,KY=0.36683502E-02,...
 DRA10=0.0,DRA20=0.0,XFFO=0.13950000E-01,...
```

```
XLLO=0.40000000E-01,MFFO=960.02734,MLLO=662.70825
CONST TEN=10.0,...
DRA11=0.0,DRA12=0.0,DRA13=0.0,DRA14=0.0,DRA15=0.0,DRA16=0.0,...
DRA17=0.0          ,DRA21=0.0,DRA22=0.0,DRA23=0.0,DRA24=0.0,...
FCL=.015,CCO=63836.395,ZGH=12.410001                    ,...
DRA25=0.0,DRA26=0.0,DRA27=0.0,HXLLO=505.81 ,HXFFO=502.34
DYNAMIC
*
*           INPUT EQUATIONS
*
VALVE=.015*RAMP(10.0)-.015*RAMP(20.0)+.51
MNN=MNNO
MAA=MAAO
TAA=TAAO
*
*           COMPUTE THE TOTAL FLUE GAS FLOW RATE INTO BOILER
*
MCC=MCCO
*
*           COMPUTE THE ENERGY ENTERING THE BOILER
*
CQ=QQO
*
*           COMPUTE THE ENERGY TRANSFERRED TO THE SCREEN RISERS
*           VIA RADIATION
*
C1=SIGMAA*((TRR+460.0)**4.0-(TVV+460.0)**4.0)
*
*           COMPUTE THE RATE EQUATION FOR FURNACE FLUE GAS
*           TEMPERATURE
*
DTRR=(CQ-C1-MRR*COR*(TRR-TAMB))/(MASSQR*COR)
*
*           COMPUTE THE FLUE GAS TEMPERATURE
*
TRR=INTGRL(TRRO,DTRR)
*
*           COMPUTE THE TEMPERATURE OF THE FLUE GAS
*           LEAVING THE SUPERHEATER
*
PHI1=2.0*MRR**0.4*CRS/KRS
TSS=(TRR*(PHI1-1.0)+2.0*TWW)/(PHI1+1.0)
*
*           COMPUTE THE SUPERHEATER ENERGY TRANSFER
*           FLUE GAS TO TUBE METAL
*
Q3=MRR*CRS*(TRR-TSS)
*
*           COMPUTE THE MAIN BANK ENERGY TRANSFER
*           FLUE GAS TO TUBE METAL
*
Q5=MSS*CST*(TSS-TTT)
*
*           COMPUTE THE TEMPERATURE OF THE FLUE GAS
*           LEAVING THE MAIN BANK
*
PHI2=2.0*MSS**0.4*CST/KST
TTT=(TSS*(PHI2-1.0)+2.0*TYY)/(PHI2+1.0)
*
*           COMPUTE THE TEMPERATURE OF THE FLUE GAS LEAVING-
*           THE ECONOMIZER
*
PHI3=2.0*CTL/KTL
TUU=(TTT*(PHI3-1.0)+2.0*TXX)/(PHI3+1.0)
*
*           COMPUTE ECONOMIZER ENERGY TRANSFER
*           FLUE GAS TO TUBE METAL
*
Q7=MTT*CTL*(TTT-TUU)
*)
```

```
*
*           USE CONTINUITY RELATIONSHIP TO COMPUTE THE MASS
*           FLOW RATE UP THE RISERS
*
MLL=MJJ-DRHOJL*VOLJL
MFF=MCC-DRHOCF*VOLCF
DRA16=DERIV(DRA10,RHOJL)
DRA28=DERIV(DRA20,RHOCF)
PROCEDURE DRHOJL=FILTR1(DRA14)
IF(KEEP.NE.1)GO TO 1
DRHOJL=(DRA18+DRA17+DRA16+DRA15+DRA14+DRA13+DRA12+DRA11+...
     DRA31+DRA32+DRA33+DRA34+DRA35+DRA36+DRA37+DRA38)/16.0
DRA53=DRA52
DRA52=DRA51
DRA51=DRA31
DRA31=DRA32
DRA32=DRA33
DRA33=DRA34
DRA34=DRA35
DRA35=DRA36
DRA36=DRA37
DRA37=DRA38
DRA38=DRA11
DRA11=DRA12
DRA12=DRA13
DRA13=DRA14
DRA14=DRA15
DRA15=DRA16
DRA16=DRA17
DRA17=DRA18
1    CONTINUE
ENDPROCEDURE
PROCEDURE DRHOCF=FILTR2(DRA24)
IF(KEEP.NE.1)GO TO 2
DRHOCF=(DRA28+DRA27+DRA26+DRA25+DRA24+DRA23+DRA22+DRA21+...
     DRA41+DRA42+DRA43+DRA44+DRA45+DRA46+DRA47+DRA48)/16.0
DRA63=DRA62
DRA62=DRA61
DRA61=DRA41
DRA41=DRA42
DRA42=DRA43
DRA43=DRA44
DRA44=DRA45
DRA45=DRA46
DRA46=DRA47
DRA47=DRA48
DRA48=DRA21
DRA21=DRA22
DRA22=DRA23
DRA23=DRA24
DRA24=DRA25
DRA25=DRA26
DRA26=DRA27
DRA27=DRA28
2    CONTINUE
ENDPROCEDURE
*
*           COMPUTE THE AVERAGE DENSITY IN THE RISERS
*
*
RHOJL=(1.0/LJL)*((LKL/(XLL*VFG))*ALOG((XLL/VF)*VFG+1.0)...
     +RHOJJ*LJK)
RHOCF=(1.0/LCF)*((LEF/(XFF*VFG))*ALOG((XFF/VF)*VFG+1.0)...
     +RHOCC*LCE)
RHOFF=RHOF-XFF*RHOFG
RHOLL=RHOF-XLL*RHOFG
*           COMPUTE THE MAIN BANK ENERGY TRANSFER -
*           TUBE METAL TO MAIN BANK MIXTURE
*
C6=KY*PSAT**(4.0/3.0)*(TYY-TSAT)**3.0
```

```
*
*          COMPUTE THE SCREEN RISER ENERGY TRANSFER -
*          TUBE METAL TO SCREEN RISER MIXTURE
*
Q2=KV*PSAT**(4.0/3.0)*(TVV-TSAT)**3.0
*
*          COMPUTE THE RISER AVERAGE ENTHALPYS
*
HDF=HDD+XFF*HFG/2.0
HJL=HJJ+XLL*HFG/2.0
*
*          COMPUTE THE RISER OUTLET ENTHALPYS
*
HFF=HF+XFF*HFG
HLL=HF+XLL*HFG
*
*          COMPUTE THE RISER EFFECTIVE HEIGHTS
*
ZDE=ZDF-LEF
ZJK=ZJL-LKL
ZKL=ZJL-ZJK
ZEF=ZDF-ZDE
*
*          COMPUTE THE SPECIFIC VOLUME OF THE ECONOMIZER
*          OUTLET LIQUID
*
VBB=.01600486-.0000020146*TBB+.000000036511*TBB**2.0...
-8.142E-11*TBB**3.0+1.403E-13*TBB**4.0-1.148E-16*TBB**5.0...
+6.034E-20*TBB**6.0
*
*          COMPUTE THE RATE EQUATION FOR RISER OUTLET QUALITY
*
DHXLL=(MGG*(HJJ-HF-XLL*HFG/2.0)+Q6-MLL*XLL*HFG/2.0)/(RHOJL*VOLKL)
HXLL=INTGRL(HXLLO,DHXLL)
XLL=(HXLL-HF)*2.0/HFG
DHXFF=(MCC*(HDD-HF-XFF*HFG/2.0)+Q2-MFF*XFF*HFG/2.0)/(RHODF*VOLEF)
HXFF=INTGRL(HXFFO,DHXFF)
XFF=(HXFF-HF)*2.0/HFG
*
*
*
*          COMPUTE THE RISER BOILING VOLUME
*
VOLEF=VOLDF*LEF/LDF
VOLKL=VOLJL*LKL/LJL
*
*          COMPUTE THE NONBOILING LENGTH OF THE RISERS
*
LDE=LDF*(HF-HDD)/((HF+XFF*HFG)-HDD)
LJK=LJL*(HF-HJJ)/((HF+XLL*HFG)-HJJ)
*
*          COMPUTE THE BOILING LENGTH OF THE RISERS
*
LKL=LJL-LJK
LEF=LDF-LDE
*
*
*
*
*          COMPUTE THE MASS RATE EQUATION FOR STEAM CONDENSING IN
*          THE DRUM
*
MCOND=560.93*(PMM/(TMM+460.0)**0.5-PSAT/(TSAT+460.0)**0.5)...
     +.02568
*
*          COMPUTE THE RATE EQUATION FOR DRUM LIQUID MASS
*
DDMASL=MLL*(1.0-XLL)+MFF*(1.0-XFF)+MCOND+MBBO-MCC-MGG
*
*          COMPUTE THE DRUM LIQUID MASS
```

```
*
DMASL=INTGRL(DMASLO,DDMASL)
*
*          COMPUTE THE RATE EQUATION FOR ENERGY IN THE DRUM LIQUID
*
DDMDHL=MLL*(1.0-XLL)*HF+MFF*(1.0-XFF)*HF+MCOND*HFG+MBB*HBB...
     -MCC*HCC-MGG*HGG
*
*          COMPUTE THE ENERGY IN THE DRUM LIQUID
*
DMDHL=INTGRL(DMDHLO,DDMDHL)
*
*          COMPUTE THE ENTHALPY OF THE DRUM LIQUID
*
DH=DMDHL/DMASL
*
*
*          COMPUTE THE DRUM SPECIFIC VOLUME
*
CRYUND=PCU*(MLL+MFF)
PROCEDURE RISE2=FILTR4(CRYUND)
RISE1=DELAY(250,RISTIM,CRYUND)
RISE2=CRYUND
IF(VALVE.GT..51)GO TO 55
RISE=RISE2
GO TO 57
55       RISE=RISE1
57       CONTINUE
ENDPROCEDURE
DDMDV=((MFF+MLL-MBB)*VF+PCU*(MFF+MLL)*VV+MBBO*VBB-(MCC+MGG)*VF+MCOND...
     *VFG-RISE*VV)
DMDV=INTGRL(DMDVO,DDMDV)
*
*          COMPUTE THE DRUM LEVEL
*
LEVEL=(DMDV-VOLDRM/2.0)/(LSTMDM*DSTMDM)
*          COMPUTE THE DOWNCOMER ENTHALPY
*
HCD=((MFF+MLL-MBB)*HF+MBB*HBB)/(MFF+MLL)
HGH=HCD
HDD=HCD
HCC=HCD
HGG=HGH
*
*          COMPUTE THE DOWNCOMER SPECIFIC VOLUME AND DENSITY
*
VCD=((MFF+MLL-MBB)*VF+MBB*VBB)/(MFF+MLL)
RHOCD=1.0/VCD
RHOGH=RHOCD
*
*          COMPUTE THE SATURATION PRESSURE AND TEMPERATURE
*          CORRESPONDING TO THE DOWNCOMER ENTHALPY
*
PSAT=EXP((ALOG(HSAT)-4.45703)/.26452)
TSAT=EXP((.22151*ALOG(PSAT)+4.77123))
*
*          COMPUTE THE ENTHALPY OF THE LIQUID ENTERING THE
*          MAIN BANK RISER
*
HJJ=HGH+Q9/MHH
*
*          COMPUTE THE RATE EQUATION FOR THE MAIN BANK AND
*          SCREEN RISER TUBE METAL TEMPERATURES
*
DTVV=(Q1-Q2)/(MASSV*CPV)
DTYY=(Q5-Q6)/(MASSY*CPY)
*
*          COMPUTE THE SCREEN AND MAIN BANK RISER TUBE
*          METAL TEMPERATURES
*
```

```
TVV=INTGRL(TVVO,DTVV)
TYY=INTGRL(TYYO,DTYY)
*
*            COMPUTE THE HEAT TRANSFER FOR THE DESUPERHEATER
*            -STEAM TO TUBE METAL
*
Q9=CNP*MNN*(TNN-TPP)
*
*            COMPUTE THE TEMPERATURE OF THE STEAM LEAVING THE
*            DESUPERHEATER
*
TPP=(TNN-TZZ)/(EXP(KNP/(CNP*MNN**0.2)))+TZZ
*
*            SET THE DOWNCOMER ENTRANCE AND EXIT TEMPERATURES
*            EQUAL TO THE SATURATION TEMPERATURE CORRESPONDING
*            TO DRUM ENTHALPY
*
TGG=TSAT
THH=TSAT
TCC=TSAT
TDD=TSAT
*
*            COMPUTE THE ENERGY TRANSFER FOR THE DESUPERHEATER
*            TUBE METAL TO DRUM LIQUID
*
Q99=KZ*(TZZ-THH)
*
*            COMPUTE THE RATE EQUATION FOR DESUPERHEATER TUBE METAL
*            TEMPERATURE
*
DTZZ=(Q9-Q99)/(MASSZ*CPZ)
*
*            COMPUTE THE DESUPERHEATER TUBE METAL TEMPERATURE
*
TZZ=INTGRL(TZZO,DTZZ)
*
*            COMPUTE THE ECONOMIZER ENERGY TRANSFER-TUBE METAL
*            TO FEED WATER
*
Q8=MAA*CAE*(TEE-TAA)
*
*            COMPUTE THE FEED TEMPERATURE AT OUTLET
*            OF ECONOMIZER
*
TBB=(TAA-TXX)/(EXP(KX/(CAP*MAA**0.2)))+TXX
*
*            COMPUTE THE RATE EQUATION FOR THE ECONOMIZER TUBE
*            METAL TEMPERATURE
*
DTXX=(Q8-Q7)/(MASSX*CPX)
*
*            COMPUTE THE ECONOMIZER TUBE METAL TEMPERATURE
*
TXX=INTGRL(TXXO,DTXX)
*
*            COMPUTE THE SUPERHEATED STEAM OUTLET TEMPERATURE
*
TNN=(TMM-TWW)/(EXP(KW/(CMN*MNN**0.2)))+TWW
*
*            COMPUTE THE SUPERHEATER ENERGY TRANSFER-TUBE METAL
*            TO STEAM
Q4=CMN*MNN*(TNN-TMM)
*
*            COMPUTE THE RATE EQUATION FOR SUPERHEATER TUBE METAL
*            TEMPERATURE
*
DTWW=(Q3-Q4)/(MASSW*CPW)
*
*            COMPUTE THE SUPERHEATER TUBE METAL TEMPERATURE
*
```

```
TWW=INTGRL(TWWO,DTWW)
*
*           COMPUTE THE IMPLICIT EQUATION FOR TOTAL STEAM
*           FLOW RATE FROM BOILER
*
MMM=IMPL(MMMO,MMME,MMMIMP)
*
*           COMPUTE THE SUPERHEATER OUTLET PRESSURE
*
PNN=SQRT(PSAT**2.0-2.0*KON3*KON1*MMM**2.0)
MMMIII=PNN*KON4*VALVE
MMMII=MNNO
MMMIMP=MMMII+MMMIII
*
*           EQUATE THE FLUE GAS MASS FLOW RATES
*
MRR=MQQ
MSS=MRR
MTT=MSS
MLL=MTT
*
*           SET RISER INLET DENSITY EQUAL TO
*           SATURATED LIQUID DENSITY
*
RHOEE=RHOF
RHOJJ=RHOF
RHOCC=RHOEE
RHOKK=RHOJJ
*
*           EQUATE DOWNCOMER FLOW RATES TO RISER ENTRANCE FLOW
*           RATES AND SET RISER ENTRANCE FLOW RATES TO THE
*           FLOW RATES AT THE INITIAL TIME
*
MHH=MGG
MCC=MDD
MGG=MJJ
MDD=MFFO
MJJ=MLLO
*
*           COMPUTE THE DERIVATIVE OF AVERAGE RISER DENSITY
*
*
*           COMPUTE THE STEAM MASS RATE EQUATION FOR THE STEAM
*           DRUM
DDSTM=XFF*MFF+XLL*MLL-MCOND-MMM
*
*           COMPUTE THE DRUM STEAM MASS
*
DSTM=INTGRL(DSTMO,DDSTM)
*
*           COMPUTE THE VOLUME OF STEAM IN THE STEAM DRUM
*
VOLSTM=VOLDRM-DMASL/RHOF
*
*           COMPUTE THE DENSITY OF STEAM IN THE STEAM DRUM
*
RHOSTM=DSTM/VOLSTM
RHOMM=RHOSTM
VVMM=1.0/RHOMM
VFGMM=VVMM-VF
*
*           COMPUTE THE STEAM DRUM STEAM OUTLET PRESSURE
*
PRESSM=524.0/(VFGMM+.1)
PROCEDURE PMM=FILTR5(PRESSM)
IF(PRESSM.LT.0.0)CALL DEBUG (3,0.0)
PMM=PRESSM
ENDPROCEDURE
*
*           COMPUTE THE STEAM DRUM STEAM OUTLET TEMPERATURE
```

```
*
TMM=EXP(.22151*ALOG(PMM)+4.77123)
*
*           SOLVE FOR THE ECONOMIZER FEED OUTLET ENTHALPY
*
HBB=(MBB*HAAO+QB)/MBB
*
*           FEEDRATE EQUATION
*
MBB=MBBO
*
*           TWO PHASE FLOW MULTIPLIER EQUATIONS
*
RGRAVE=24.794*XFF**2.0-6.5066*XFF+.9776
RGRAVK=24.794*XLL**2.0-6.5066*XLL+.9776
RACLE=15.4564*XFF**2.0+18.4944*XFF-.00007
RACLJ=15.4564*XLL**2.0+18.4944*XLL-.00007
RFRICE=-34.0822*XFF**2.0+23.7164*XFF+.8734
RFRICK=-34.0822*XLL**2.0+23.7164*XLL+.8734
*
*           STATE POINT EQUATIONS
*
HSAT=DH
HF=HSAT
HFG=922.15-0.40516*PSAT+1.717E-04*PSAT**2.0-4.219E-08...
     *PSAT**3.0
HV=HSAT+HFG
RHCF=63.8-0.01781*TSAT+1.132E-05*TSAT**2.0-6.786E-08...
```

G. Anticipated Performance

	Endurance 2 Boilers	Design Rated Full Power	Maximum Intermittent Power	Endurance 1 Boiler	Boiler Overload
Rate of Operation - Per Cent	56	83	97	114	120
Total Steam Generated lb/hr	195,000	290.000	340,000	400.000	420.000
Superheated Steam lbs/hr.	155,000	235,000	265.000	300,000	320.000
Desuperheated Steam lbs/hr.	40,000	55,000	75,000	100,000	100.000
Boiler Drum Pressure psig	690	690	690	690	690
Superheater Outlet Pressure psig	665	630	610	580	570
Superheater Outlet Temperature °F	912	914	980	898	895
Desuperheated Steam Outlet Pressure psig	651	606	558	480	470
Desuperheated Steam Outlet Temperature °F	635	659	680	690	690
Economizer Inlet Pressure psig	715	726	733	749	754
Economizer Inlet Temperature °F	250	250	250	250	250
Economizer Outlet Pressure psig	703	705	703	708	710
Economizer Outlet Temperature °F	355	372	372	377	380
Casing Air Inlet Temperature °F	100	100	100	100	100
Total Air Flow lb/hr	242,229	368.092	433,589	513.154	540.952
Total Oil Flow lb/hr	14,333	21,781	25,656	30,364	32,009
Anticipated Efficiency %	85.7	84.4	83.8	83.0	82.7
Guaranteed Efficiency %	85.7	84.4	83.8	83.0	82.7
Radiation and Unaccounted for Losses %	.99	.99	.95	1.01	.98
Excess Air %	15.0	15.0	15.0	15.0	15.0
Carbon Dioxide %	13.0	13.0	13.0	13.0	13.0
Number of Burners in Operation	6	6	6	6	6
Throttle or Non-Throttle of Air Doors	N.T.	N.T.	N.T.	N.T.	N.T.
Draft Loss - Total Inches Water	13.74	33.98*	47.96	69.51	76.22** 93.48***
Through Double Casing	1.33	3.09	4.28	6.00	6.67 10.22
Through Burner Register	2.60	6.00	8.50	11.50	13.00 15.88
Through Boiler & Superheater	4.83	12.29	18.14	25.61	28.15 38.32
Through Economizer	4.98	12.60	17.04	26.40	28.40 29.06
Gas Temperature Leaving Superheater Screen °F	2471	2594	2642	2686	2699
Gas Temperature Leaving Superheater °F	1826	1961	2021	2085	2103
Gas Temperature Leaving Main Bank °F	694	774	812	856	872
Gas Temperature Leaving Economizer °F	373	427	453	484	498
Heat Release KB/Hr/Sq. Ft. Radiant Heat Absorbing Surface	447	680	800.6	948	999
Heat Release KB/Hr/Sq. Ft. Total Heating Surface	15.5	23.6	28.0	32.9	34.7
Heat Release KB/Hr/Cu. Ft. Furnace Volume	183.9	279.5	329.2	389.6	410.8
Furnace Heat Absorption KB/Hr./Sq. Ft	128.4	171.0	191.1	213.19	221.5
Heat Absorption First Water Screen Row KB/Hr/Sq. Ft. (Max.)	210	231	255.3	288	256
Heat Absorption Maximum KB/Hr./Sq. Ft (Furnace Screen)	210	231	255.3	288	256

*Draft Losses (Full Power) Based On 241 Cu. Ft. of 100°F Air/Lb. of Fuel Oil

**Draft Losses (Overload) Based On 241 Cu. Ft. of 100°F Air/Lb. of Fuel Oil

***Draft Losses (Overload) Based on 260 Cu. Ft. of 68°F Air/Lb. of Fuel Oil

II. Anticipated Metal Temperature Degree F.

	Endurance 2 Boilers	Design Rated Full Power	Maximum Intermittent Power	Endurance 1 Boiler	Boiler Overload
Water Screen Tubes Outside	644	656	661	667	680
Water Screen Tubes Inside	554	554	554	554	555
Superheater Tubes Outside - Maximum	1022	1046	1049	1048	1046
Superheater Tubes Inside - Maximum	1044	1020	1019	1014	1012
Maximum Inner Casing Temperature	800	825	835	850	870
Maximum Outer Casing Temperature at way of Structural ties	350	350	350	350	350
Maximum Outer Casing Temperature	145	145	145	145	145

I. Tube Data

	O.D.	M.W.T.	No.	Material
Side Wall and Roof	2"	.134"	71	MIL-T-16286 CL. A*
Rear Wall	2"	.134"	54	MIL-T-16286 CL. A*
Front Wall	2"	.134"	22	MIL-T-16286 CL. A*
Screen Bank	2"	.134"	102	MIL-T-16286 CL. A*
Superheater	1.5"	.120	22	MIL-T-16286 CL. E
Main Bank	2"	.134"	34	MIL-T-16286 CL. A*
Main Bank	1"	.085"	2808	MIL-T-16286 CL. A*
Economizer	2"	.180"	182	MIL-T-16286 CL. A
Desuperheater (in Water Drum)	2"	.220"	6	SA-268 TP-430
Downcomers	8 5/8"	.483"	1	Schedule 80 Pipe ASME SA-106-B
Downcomers	10 3/4"	.519"	5	Schedule 80 Pipe ASME SA-106-B
Downcomers	12 3/4"	.601	2	Schedule 80 Pipe ASME SA-106-B
Risers	6"	.500"	7	ASME SA-106-B

*These tubes may be MIL-T-16286, Class A (Seamless) or MIL-T-17188 (Seamed) electric resistance welded.

LIST OF REFERENCES

1. Fini, W. P., A Computer Simulation of a Naval Boiler, Masters Thesis, Naval Postgraduate School, Monterey, CA, 1978.

2. Oak Ridge National Laboratory Report ORNL-TM-4248 ORCON 1: A FORTRAN Code for the Calculation of a Steam Condenser of Circular Cross Section, by J. A. Hafford, July 1973.

3. Grimson, E. D., "Correlation and Utilization of New Data on Flow Resistance and Heat Transfer for Cross Flow of Gases over Tube Banks," Trans. ASME, Vol. 59, pp. 583-594, 1937.

4. Weierman, C., and others, Comparison of the Performance of Inline and Staggered Banks of Tubes with Segmented Fins, paper presented at the Fifteenth National Heat Transfer Conference, AIChE-ASME, San Francisco, CA, August 10-13, 1975.

5. Tong, L. S., Boiling Heat Transfer and Two Phase Flow, p. 118, Wiley, 1965.

6. Dittus, F. W., and Boelter, L.M.K., University of California (Berkeley) Pub. Eng., Vol. 2, p. 443, 1936.

7. Signell, W. I., Marine Boiler Design Today, paper presented at Annual Meeting of The Society of Naval Architects and Marine Engineers, New York, NY, November 13-16, 1968.

8. Weitzel, P., Telecon, Subject: Dynamic Modeling of Boiler Shrink and Swell Phenomena, 13 June, 6 July, 9 July, 17 July, 20 August 1979.

9. Leondes, C. T., and others, Control and Dynamic Systems, Vol. 14, p. 175, Academic Press, 1978.

10. Thom, J.R.S., Prediction of Pressure Drop During Forced Circulation Boiling of Water, International Journal of Heat and Mass Transfer, Vol. 7, p. 709-724, Pergamon Press, 1964.

11. Schlichting, H., Boundary Layer Theory, 6th ed., McGraw Hill, 1968.

12. Rohsenow, W. M., and P. Griffith, "Correlation of Maximum Heat Flux Data for Boiling of Saturated Liquids," AICHE-ASME Heat Transfer Symp., Louisville, Ky., 1955.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 69 Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93940	2
4.	Dr. Thomas M. Houlihan, Code 69Hm Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93940	5
5.	Lieutenant Thomas D.L. Walker USN Department of Mechanical Engineering Code 69 Naval Postgraduate School Monterey, California 93940	2
6.	Paul Weitzel Babcock and Wilcox 20 South Van Buren Avenue Barberton, Ohio 44203	1
7.	Mr. Thomas Graf Code 67230 Naval Ship Engineering Center Philadelphia, PA 19112	1